**Urban Development**
Princetonlaan 6
3584 CB Utrecht
P.O. Box 80015
3508 TA Utrecht
The Netherlands

www.tno.nl

T +31 88 866 42 56
F +31 88 866 44 75
infodesk@tno.nl

**TNO report**

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# Dose-response relationship between *DNL* and aircraft noise annoyance: contribution of TNO

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| Date | 19 May 2011 |
| Author(s) | Sabine A. Janssen<br>Henk Vos |
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# 1 Introduction

The human need for transportation by air has been growing rapidly for several decades and is predicted to keep growing in the future. Aircraft noise may induce annoyance, which has been recognized by policy makers as a harmful effect that should be prevented and reduced. Over the years, many aircraft noise annoyance surveys have been conducted, and attempts have been made to integrate the results through meta-analyses with the aim of establishing dose-response curves describing the relationship between aircraft noise exposure and annoyance, where the percentage of persons annoyed by aircraft noise is related to the noise exposure level (Schultz, 1978; Kryter, 1982; 1983; Fidell et al., 1991; Miedema and Vos, 1998; Miedema and Oudshoorn, 2001). These dose-response relationships can be used to predict the level of annoyance of aircraft noise in a given population, which is needed for noise impact analyses and for developing socially optimal mitigation solutions. By applying the relationships to various future alternatives and the existing situation, the noise impacts of the alternatives can be compared with each other and with the present situation. However, the noise exposure situation around airports has changed considerably, and there is evidence that the annoyance response at a given exposure level has increased. Currently, the dose-response relationship between DNL and annoyance due to aircraft noise is being updated within the framework of the ISO Working Group 45, with complementary research looking into several situational factors that may influence the community response to aircraft noise. In the present report, a short overview of the state of the art on dose-response relationships for aircraft noise annoyance is presented, including the evidence on factors that may influence annoyance in addition to energy equivalent noise metrics such as DNL, as well as the evidence for increased annoyance due to aircraft noise over time. Subsequently, an analysis is presented on the influence of individual characteristics of the respondents on their aircraft noise annoyance. Also, a relationship is given between DNL and aircraft noise annoyance based on an analysis on the overlapping part of the datasets of TNO and the ISO Working Group 45 in order to be able to compare the outcomes of the different approaches. The final chapter contains a discussion of the strengths and weaknesses of both methods and their application in policy.

# 2 Review of TNO analyses on aircraft noise annoyance

## 2.1 Dose-response relationships due to transportation noise, including aircraft noise

On the basis of a large number of studies into noise annoyance arising from community transportation, separate dose-response relationships were derived for (high) annoyance by aircraft, road and rail traffic noise, as described in Miedema and Oudshoorn (2001). Miedema and Oudshoorn (2001) fitted a model of annoyance as a function of noise exposure to the original data from a very large set of field studies in which noise exposure and noise annoyance were available for each respondent. The database used contains all studies examined earlier in the syntheses by Schultz (1978) and Fidell, Barber, and Schultz (1991) provided that *DENL* or *DNL* and percentage highly annoyed could be assessed while meeting certain minimal requirements. In addition, many other studies were included. Different functions were found for aircraft, road traffic, and railway noise, with the rate of increase being 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 functions do not overlap at higher exposure levels. The resulting relationships for *DENL*, shown in Figure 1, were recommended in an EU position paper published in 2002 (EC, 2002), stipulating European Union policy regarding the quantification of annoyance due to transportation noise. They can be used in Environmental Health Impact Assessment and cost-benefit analysis to translate noise maps into overviews of the numbers of persons annoyed (or highly annoyed), thereby giving insight into the situation expected in the long term. They are not applicable to local complaint-type situations, or to an assessment of the short-term effects of a change in noise climate.

Similar curves were derived for the relationship between *DNL* and the annoyance response. In order to ease application of the curves, (very close) polynomial approximations are given for the model. It should be noted, however, that the "polynomial look" of these curves is not the result of a polynomial fit to the observed data, but is the outcome of the grouped regression model on the individual data points (described shortly in Chapter 4 of this report and explained in Miedema and Oudshoorn (2001); Groothuis-Oudshoorn and Miedema (2006)). Using this statistical model, both the between-study variance and the individual variance (between respondents within studies) is taken into account, enabling the correct derivation of 95% confidence intervals around the curves. Another advantage of this statistical method is that the entire annoyance distribution is modeled, enabling the estimation of not only the percentage of highly annoyed people (*%HA*), but also the percentage of annoyed (*%A*) or a little annoyed (%LA) people. The polynomial approximations for the relationship between *DENL* or *DNL* and these annoyance measures for aircraft noise are given below:

$$\%LA \text{ Aircraft: } -6.158 \times 10^{-4} (DENL - 32)^3 + 3.410 \times 10^{-2} (DENL - 32)^2 + 1.738 (DENL - 32)$$
$$\%A \text{ Aircraft: } 8.588 \times 10^{-6} (DENL - 37)^3 + 1.777 \times 10^{-2} (DENL - 37)^2 + 1.221 (DENL - 37)$$
$$\%HA \text{ Aircraft: } -9.199 \times 10^{-5} (DENL - 42)^3 + 3.932 \times 10^{-2} (DENL - 42)^2 + 0.2939 (DENL - 42)$$

$$\%LA \text{ Aircraft: } -5.741 \times 10^{-4} (DNL - 32)^3 + 2.863 \times 10^{-2} (DNL - 32)^2 + 1.912 (DNL - 32)$$
$$\%A \text{ Aircraft: } 1.460 \times 10^{-5} (DNL - 37)^3 + 1.511 \times 10^{-2} (DNL - 37)^2 + 1.346 (DNL - 37)$$
$$\%HA \text{ Aircraft: } -1.395 \times 10^{-4} (DNL - 42)^3 + 4.081 \times 10^{-2} (DNL - 42)^2 + 0.342 (DNL - 42)$$

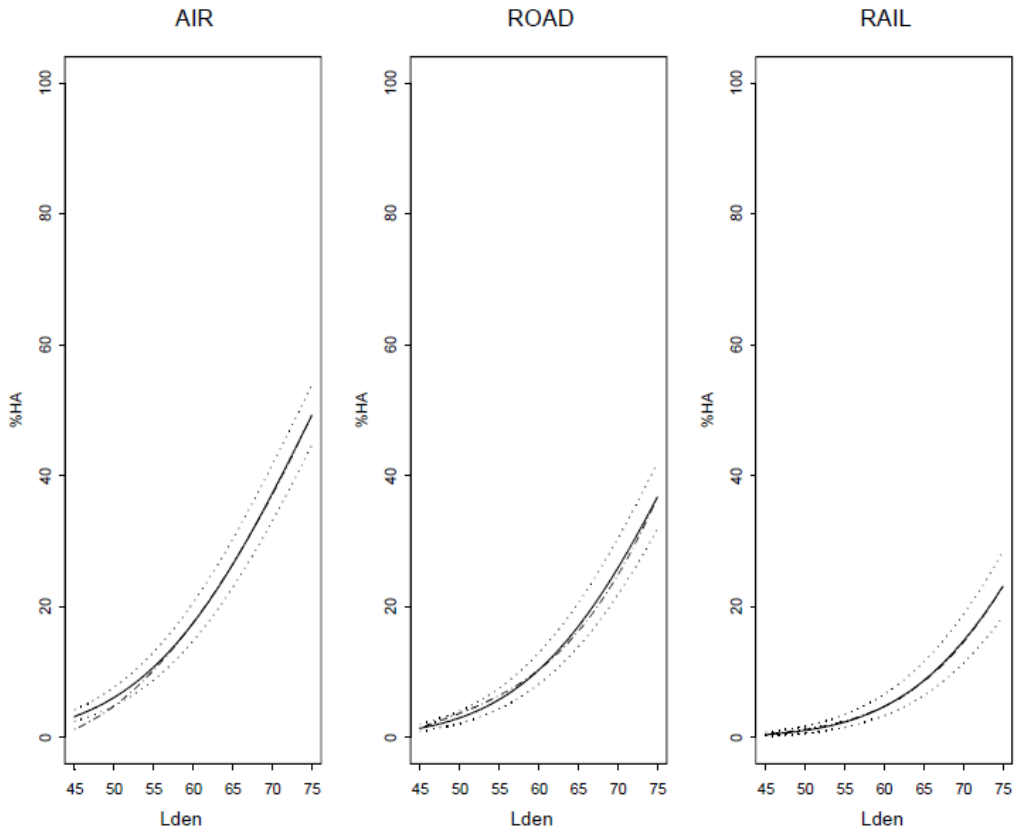



**Figure 1:** The percentage of highly annoyed persons (*%HA*) due to transportation noise as a function of noise exposure at the façade of the dwelling $L_{den}$ (i.e. *DENL*). The solid lines are the estimated curves (with 95% confidence intervals in dotted lines), and the dashed lines are polynomial approximations (taken from EU position paper 2002).

## 2.2 Trends in annoyance due to aircraft noise

Recently, evidence has appeared of an increase over the years in the annoyance of residents at a given aircraft noise exposure level (Guski, 2004; van Kempen and van Kamp, 200; Babisch et al., 2009). Indeed, an analysis on the basis of the database used to establish earlier dose-response relationships, updated with original data from 7 recent surveys, indicated a significant increase over the years in expected annoyance at a given level of aircraft noise exposure (Janssen et al., 2011). Instead of a gradual increase, annoyance appeared to show an increase from around 1996 onward. Although several study characteristics were found to be sources of heterogeneity in annoyance response, such as the type of annoyance scale, the type of contact, and the response percentage, none of these factors could satisfactorily explain the effect of the year of the study. Other possible explanations for the year effect, such as the higher rate of expansion of airports in recent years, or changes in the noise emitted by individual aircraft (accompanied by an increase in the number of overflights at the same *DENL* or *DNL* level) could neither be confirmed nor ruled out. Also, no evidence was found for increased self-reported noise sensitivity, which is in line with the absence of indications for a similar increase in annoyance due to other noise sources. Although the reasons are not yet fully understood, it seems that one or more factors specific for aircraft noise may be held responsible.

A follow-up analysis (Janssen and Vos, 2009) aimed to quantify the increase in annoyance observed in recent aircraft noise surveys with respect to the exposure-response relationship based on older surveys. To this end, the 7 recent original noise survey datasets in the dataset (1996 and later) were compared to earlier studies. The same method was used as in Miedema and Oudshoorn (2001), however by including a dummy variable for the recent studies (as well as an interaction between this dummy and *DENL* to account for possible differences in slope) the effect estimates were determined of the relationship between exposure and annoyance for the recent and earlier studies separately. This comparison revealed a significant increase in annoyance in the 7 recent studies as compared to the earlier studies at a given level of aircraft noise exposure (see Figure 2). For instance, at a *DENL* level of 55 dB(A), the exposure-response curve indicates an expected percentage of annoyed persons of 28%, while recent studies put the percentage of annoyed persons at 50%. This analysis, which reflects four decades of aircraft noise annoyance research, yields an estimation of the size of the increase compared to earlier exposure-response relationships for aircraft noise and provides a basis for decisions on whether the exposure-response relationships for aircraft noise need to be updated. Given the large part of heterogeneity explained by the year of the study, it does not seem justifiable to pool recent and older studies into one single relationship. While an update of the dose-response relationship for aircraft noise based exclusively on recent studies may be foreseen in the near future, it is considered premature at this stage in the face of uncertainties regarding the causes and the extent of the change.

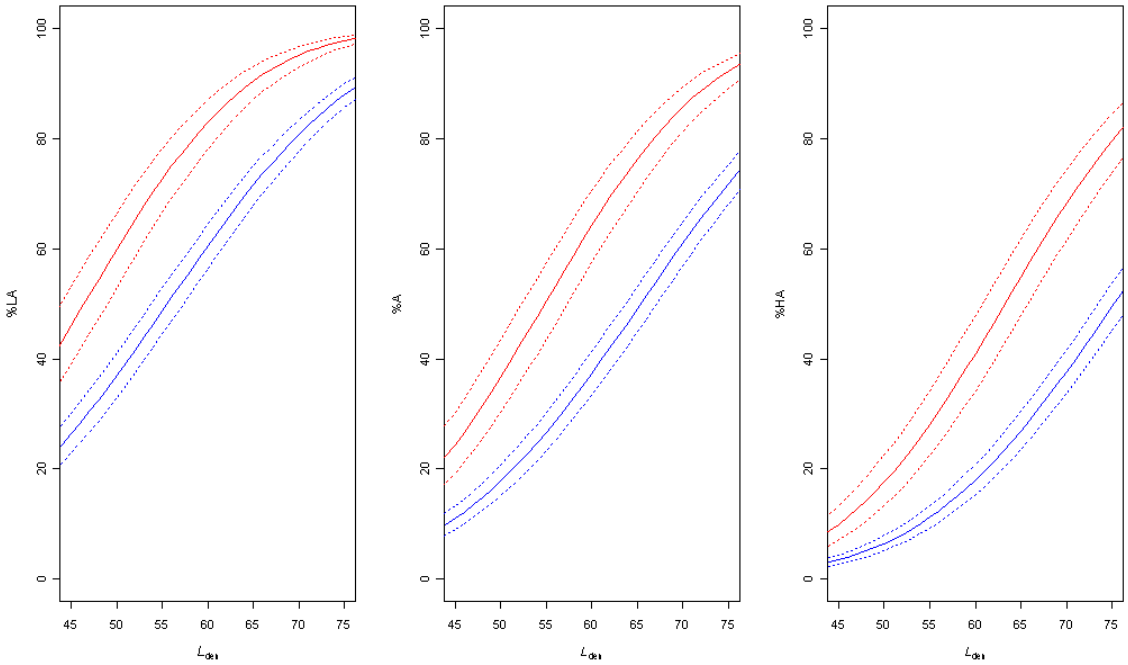



**Figure 2:** *%LA*, *%A* and *%HA* for the 'older' (blue) and for the recently added datasets (red) with their confidence intervals (dotted line) as a function of $L_{den}$ (i.e. *DENL*).

## 2.3 The influence of non-acoustic (demographic and attitudinal) factors

Miedema and Vos (1999) investigated the possible systematic effects of non-acoustic factors on noise annoyance, reporting consistent results with the meta-analysis conducted by Fields (1993). They presented quantitative estimates of the effects on annoyance of non-acoustical factors in addition to *DENL*. The results are based on analyses of the original data from various field surveys of responses to noise from transportation sources for which information on

demographic and attitudinal factors was available for each respondent (number of cases depending on the variable between 15 000 and 42 000). It was found that fear has a very large impact on annoyance. Persons who experience fear related to the transportation that causes the noise, report higher annoyance compared to persons who do not experience such fear. With three categories of fear, the annoyance difference between the lowest and the highest fear level was found to be equivalent to a *DENL* difference of (at most) 19 dB(A). The effect of fear on annoyance is found for all three modes of transportation, although only few persons appear to associate high fear with railway traffic. Another important factor is noise sensitivity, a personal trait that is stable over time and only has a very weak relationship with noise exposure (see also Miedema and Vos, 2003). The annoyance difference between the highest and lowest of three noise sensitivity categories was found to be equivalent to a *DENL* difference of 11 dB(A). Demographic factors are much less important than fear and noise sensitivity. Noise annoyance is not related to gender, but age has an effect on noise annoyance. The largest difference in annoyance between (seven) age classes is equivalent to a *DENL* difference of circa 5 dB(A). At the same noise exposure level relatively young and relatively old persons are less annoyed than the ages in between (see also van Gerven et al., 2009). Higher annoyance is reported if the education is higher, the occupational status is higher, the dwelling is owned instead of rented, if a person does not depend on the noise source, and if the use of the transportation that causes the noise is low. In addition, a person in a household consisting of two persons reports more annoyance than a person in a household of another size, also if the age of the person is taken into account. However, the effects of these factors on noise annoyance are small, i.e., the equivalent *DENL* difference is equal to 1-2 dB(A), and, in the case of dependency,
3 dB(A).

## 2.4 The tradeoff between noise levels of overflights

An important question regarding dose-response relationships for aircraft noise annoyance is whether the annoyance due to infrequent high levels of noise events is the same as the annoyance caused by frequent moderate levels at the same *DENL* or *DNL*. By using $L_{Aeq}$-based metrics such as *DENL* or *DNL* for the prediction of annoyance, it is implicitly assumed that the effect of doubling the number of events on annoyance can be exactly offset by a 3-dB reduction of the level (SEL) of events. This was tested by Miedema, Vos and de Jong (2000) on the basis of the data from NET-371 (Amsterdam Schiphol Airport Study, 1996). This dataset is very suitable for investigating the tradeoff assumption, because the distribution of the levels (in SEL) of the individual noise events is known for each subject and can be related to the annoyance reported by this subject. Based on the data of over 11000 respondents, values of the tradeoff parameter optimal for the prediction of annoyance were estimated. It was concluded from the results that the tradeoff between levels of overflights in $L_{Aeq}$-based metrics such as *DENL* or *DNL* is approximately correct for the prediction of noise annoyance.

# 3 Data used in the analyses

**Table 1:** Study Characteristics: Study ID (code assigned by Fields, see Wiley (2009)), Name of the survey, Reference (report or publication of the survey, Airports (number of airports in survey), N, year of the survey (*Year*), type of contact (*Contact*: 1= postal, 2= telephone, 3= face-to-face), response percentage (*Resp*), number of categories of annoyance scale(s) used in the survey (*Scale*).

| Study ID | Name of the survey | Reference | Airports | N | Year | Contact | Resp | Scale |
|---|---|---|---|---|---|---|---|---|
| AUL-210 | Australian Five Airport Survey | Bullen et al., 1986 | 5 | 3206 | 1980 | 3 | 82.0 | 5 |
| CAN-168 | Canadian National Community Noise Survey | Hall et al., 1981 | 1 | 631 | 1978 | 3 | 75.0 | 11 |
| FRA-016 | French Four-Airport Noise Study | Alexandre et al, 1970 | 4 | 1301 | 1966 | - | - | 4 |
| FRA-239 | French Combined Aircraft/Road Traffic Survey | Vallet et al., 1986 | 1 | 565 | 1984 | 3 | - | 10 |
| GER-531 | Frankfurt Airport Survey | Schreckenberg et al,. 2010 | 1 | 2235 | 2005 | 3 | 61.0 | 11 |
| NET-240 | Schiphol Combined Aircraft/Road Traffic Survey | Diamond et al., 1986 | 1 | 573 | 1984 | 3 | 46.0 | 10 |
| NOR-311 | Oslo Airport Survey | Gjestland et al., 1990 | 1 | 1396 | 1989 | 2 | 52.0 | 4 |
| NOR-328 | Bodo Military Aircraft Exercise Study | Gjestland et al., 1993b | 1 | 673 | 1992 | 2 | 51.0 | 4 |
| NOR-366 | Vaernes Military Aircraft Exercise Study | Gjestland et al., 1993a | 1 | 321 | 1990 | 2 | - | 4 |
| SWE-035 | Scandinavian Nine-Airport Noise Study | Rylander et al, 1972 | 9 | 1491 | 1972 | - | - | 4 |
| SWI-053 | Swiss Three-City Noise Survey | Graf et al,1974 | 3 | 3076 | 1972 | - | - | 11 |
| SWI-525 | Zurich Airport Survey | Brink et al., 2008 | 1 | 1382 | 2001 | 1 | 52.0 | 11 |
| SWI-534 | Zurich Airport Survey (Follow-up) | Brink et al., 2008 | 1 | 1242 | 2003 | 1 | 52.0 | 11 |
| UKD-024 | Heathrow Aircraft Noise Survey | Knowler, 1971 | 1 | 3845 | 1967 | 3 | - | 4 |
| UKD-238 | Glasgow Combined Aircraft/Road Traffic Survey | Diamond and Walker, 1986 | 1 | 598 | 1984 | 3 | - | 10 |
| UKD-242 | Heathrow Combined Aircraft/Road Traffic Survey | Brooker and Richmond, 1985 | 4 | 1993 | 1981 | 3 | - | 4 |
| USA-022 | U.S.A. Four-Airport Survey (phase I of Tracor Survey) | Hazard, 1971 | 4 | 2235 | 1967 | 3 | 79.0 | 5 |
| USA-032 | U.S.A. Three-Airport Survey (phase II of Tracor Survey) | Hazard, 1971 | 3 | 1540 | 1969 | 3 | - | 5 |
| USA-044 | U.S.A. Small City Airports (Small City Tracor Survey) | Pattersen and Connor, 1973 | 2 | 1612 | 1971 | 3 | - | 5 |
| USA-082 | LAX Airport Noise Study | Fidell and Jones, 1975 | 1 | 374 | 1973 | 2 | - | 5 |
| USA-203 | Burbank Aircraft Noise Change Study | Raw and Griffiths, 1985 | 1 | 586 | 1979 | 3 | 80.0 | 5 |
| USA-204 | John Wayne Airport Operation Change Study | Fidell et al,1982 | 1 | 601 | 1981 | - | - | 5 |
| USA-338 | USA Air Force Base Study | Borsky,1983 | 7 | 839 | 1981 | 1 | - | 10 |

**Table 2:** Wording of the annoyance question for studies in the analysis

| Study ID | Wording of the annoyance question |
|---|---|
| AUL-210 | How would you describe your general feelings about the aircraft noise in this neighborhood? would you say you are 1=highly 2=considerably 3=moderately 4=slightly 5=not at all annoyed |
| CAN-168 | On this scale from 0(not at all disturbed) to 10 (unbearably disturbed), how do you rate aircraft noise and the overall noise |
| FRA-016 | Are you annoyed by aircraft noise? Not at all, a little, moderately, much |
| FRA-239 | Just to make sure I have it all straight, how do you feel overall about the noise from aircraft? Not at all annoyed=1--- 10=Very much annoyed |
| GER-531 | Here I have a measuring scale from 0 till 10, where you can indicate how much you are annoyed by Aircraft noise. When you feel extremely annoyed choose 10, when you are not at all annoyed choose 0. When you are in between pleas choose a number between 0 and 10. When you think about the past 12 months, which number represents how much you were annoyed by Aircraft noise in total?. not at all=0 --- 10=extremely. |
| NET-240 | Just to make sure I have it all straight, how do you feel overall about the noise from aircraft? Not at all annoyed=1--- 10=Very much annoyed |
| NOR-311 | Do you consider this noise: 1=very annoying 2=quite annoying 3=a little annoying 4=not annoying |
| NOR-328 | When at home do you hear noise from Aircraft? if YES : Do you consider this noise: 1=very annoying 2=quite annoying 3= a little annoying or 4:not annoying? |
| NOR-366 | When at home do you hear noise from Aircraft? if YES : Do you consider this noise: 1=very annoying 2=quite annoying 3= a little annoying or 4:not annoying? |
| SWE-035 | How much are you annoyed by aircraft noise?' (Does not notice, Notice but not annoyed, a little annoyed, rather annoyed, very annoyed.) |
| SWI-053 | Let's assume that this would be a thermometer with which it is possible to measure how much aircraft noise disturbs you at home. The number ten (10) means that you find aircraft traffic noise unbearable, the number zero (0) that it doesn't disturb you at all. Please tell me the number that applies to you. |
| SWI-525 | Here we have a scale on which you can indicate how much aircraft noise has disturbed you or annoyed you. When you are very disturbed or annoyed, you can mark the 10, when you are not disturbed or annoyed at all you can mark the 0,when you are somewhere in between, please mark a number between 0 and 10. not at all=0---10=extremely. |
| SWI-534 | Here we have a scale on which you can indicate how much aircraft noise has disturbed you or annoyed you. When you are very disturbed or annoyed, you can mark the 10, when you are not disturbed or annoyed at all you can mark the 0,when you are somewhere in between, please mark a number between 0 and 10. not at all=0---10=extremely. |
| UKD-024 | (show card A) Please look at the scale and tell me how much the noise of the aircraft bothers or annoys you (ordinary flights, not sonic boom) 1=Very much 2=Moderately 3=A little 4=Not at all |
| UKD-238 | Just to make sure I have it all straight, how do you feel overall about the noise from aircraft? Not at all annoyed=1--- 10=Very much annoyed |
| UKD-242 | Please look at this scale and tell me how much the noise of aircraft here bothers or annoys you 1.Very much 2.Moderately 3.A little 4.Not at all |
| USA-022 | Now I will read a list of sounds and sources of sounds. For each one, please tell me whether it is a kind of sound you hear in this neighborhood; and if so, how often you find it annoying. Use the opinion thermometer to rate your feeling of annoyance and to rate how often you feel annoyed. . Not at all/none A little, Somewhat, Very, Extremely |
| USA-032 | Of those that you hear, how much are you bothered or annoyed? Use the opinion thermometer. . Not at all/none A little, Somewhat, Very, Extremely |
| USA-044 | Of those that you hear, how much are you bothered or annoyed? Use the opinion thermometer. Not at all/none A little, Somewhat, Very, Extremely |
| USA-082 | Are you ever annoyed by aircraft noise in your neighborhood? 0=not at all annoyed 1=slightly annoyed 2=moderately annoyed 3=very annoyed 4=extremely annoyed 8=don know 9=not applicable |
| USA-203 | While you've been at home over the past YEAR(since this time last year), would you say that you've been not at all annoyed by aircraft noise, slightly annoyed not Annoyed=1--5=Extremely Annoyed |
| USA-204 | While you've been at home during the past week, have you been bothered or annoyed by the noise of large airliners? IFYES ASK: Would you say that you've been not at all, slightly, moderately or extremely annoyed by noise from large airliners? |
| USA-338 | How much does noise from aircraft disturb, bother, or annoy you? Not at all= 0..9= Extremely |

# 4 Analyses on individual data

## 4.1 Statistical model for deriving the dose-response relationship

This method has been used before and is described in detail by Miedema and Oudshoorn (2001) and Groothuis-Oudshoorn and Miedema (2006).

The analysis is done on the individual data, using *DNL* and the annoyance score recoded into a 0-100 point score of each individual respondent. Extreme exposure levels (*DNL* < 45 or > 75 dB) are excluded, because the risk of unreliable data is high at very low levels, whereas the risk of survivors is high at very high levels. The annoyance boundary quantifications are computed for each collected annoyance score. For scales with various numbers of categories the boundaries are as follows:

| 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 | 0-10-20-30-40-50-60-70-80-90-100 |
| 11 | 0-9-18-27-36-45-55-62-73-82-91-100 |

The model we fit is (using individual index i and study index j):

$$A_{ij} = \beta_0 + \beta_1 DNL + u_{0j} + \varepsilon_{ij} \qquad [1]$$

We use a regression method allowing for the inclusion of a random effect $u_{0j}$. Using this regression method we model the annoyance score on a 100-point scale (or rather its boundaries) for each respondent as a function of the exposure level. By using the 100-point score as a continuous dependent variable (divided into intervals) instead of a dichotomized high annoyance cutoff point, all the information of the data distribution is used. The regression model, apart from getting estimates for the model parameters, also estimates the variance accounted for by the random effect (airport, study) $s^2_0$ as well as estimates for the individual variance (at the respondent level), $s^2_1$.

After fitting the regression including a random effect for each airport or study we get estimates for $\beta_0$, $\beta_1$, $\sigma^2_0$ and $\sigma^2_1$ by which the annoyance score may be predicted. Still, the probability to exceed a certain annoyance score at a given *DNL* level (*%A* or *%HA*) may be more important for policy than the mean annoyance score. For any value of the exposure variable, the expected percentage annoyed (*%A*) and the percentage highly annoyed (*%HA*) can be estimated from the regression coefficients $b_0$ and $b_1$, and variance components $s^2_0$ and $s^2_1$ by using equation [6] from Miedema and Oudshoorn (2001). Confidence intervals for *%A* and *%HA* may be obtained by multiplying the covariance matrix of the parameter estimates of $\beta_0$ and $\beta_1$ and the exposure values according to Miedema and Oudshoorn, equation [7].

## 4.2 Estimating the influence of covariates:

By extending formula [1] we can also estimate the effects of covariates. The model we get is:

$A_{ij} = \beta_0 + \beta_1 DNL + \beta_2 \text{COVARIATE} + u_{0j} + \varepsilon_{ij}$

This implies we will get estimates for the amount of shift in the relationship between *DNL* and *A* expected for each covariate, which will be translated into equivalent dB(A) differences to indicate the size of the influence of a certain covariate.

The influence of the following covariates is estimated on an individual basis:

- AGE
- GENDER
- EDUCATION (ISCED classification)
- OCCUPATION (a ranked order of profession as a proxy for SES)
- HOUSEHOLD SIZE
- HOMEOWNERSHIP
- DEPENDENCY (does respondent depend on the noise maker, eg. for work)
- USE OF SOURCE (frequency of use)
- NOISE SENSITIVITY
- FEAR (of the source causing the noise)

In the same manner, study characteristics may be included as covariates. In the present analysis, the influence of YEAR (recent versus older studies) is tested because of the earlier findings of a trend in annoyance by aircraft noise over time.

## 4.3 Summary of the TNO-approach:

- The exposure-annoyance relationship is modelled with a (censored*) grouped regression method where study is included in the model as a random factor. The analysis is done on individual data points.
- Additional variables may be entered into the model to assess the influence of individual and study differences, which may be translated into dB(A) equivalents.
- From the results of the fitted model, *%A* and *%HA* can be calculated using the regression coefficients $b_0$ and $b_1$, and variance components $s^2_0$ and $s^2_1$.
- The calculated values of *%A* and *%HA* for *DNL* levels [45:75] based on the model may be used to fit polynomial approximations.

* The dispersion level of the annoyance score varies with the noise exposure: for low levels (*DNL* just above 45) and high levels (*DNL* just below 75) the annoyance is expected to vary less among people than at intermediate levels. A distribution with bounded support on [0-100] and a variation related to *DNL* as described is a *censored* normal distribution. Therefore, a regression model capable of analyzing censored data is used.

## 4.4 Variables used in the analysis

**Table 3:** Overview of variables in the analysis showing mean values or percentages of respondents per category

| | | | | | | | Household size% | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Study ID | airport | *DNL* | annoyance | N | Age | Male% | 1 | 2 | 3 | 4 | >=5 |
| AUL-210 | ADL | 62.5 | 45.2 | 591 | 45.9 | 44 | | | | | |
| | MLB | 59.9 | 39.2 | 325 | 35.9 | 39 | | | | | |
| | PER | 60.1 | 32.5 | 626 | 43.1 | 42 | | | | | |
| | RCM | 64.4 | 41.0 | 281 | 41.7 | 49 | | | | | |
| | SYD | 64.2 | 52.4 | 1383 | 43.7 | 44 | | | | | |
| CAN-168 | YYZ | 63.0 | 46.6 | 631 | 38.0 | 35 | | | | | |
| FRA-016 | 4 CI | 63.6 | 39.5 | 1301 | | | | | | | |
| FRA-239 | ORY | 59.9 | 53.3 | 565 | 40.9 | 42 | 7 | 26 | 26 | 26 | 15 |
| GER-531 | FRA | 57.0 | 49.0 | 2235 | 51.7 | 45 | 15 | 45 | 18 | 16 | 6 |
| NET-240 | AMS | 60.2 | 43.8 | 573 | 43.8 | 44 | 18 | 36 | 18 | 19 | 9 |
| NOR-311 | FBU | 58.5 | 40.6 | 1396 | 44.8 | 47 | 24 | 32 | 17 | 19 | 8 |
| NOR-328 | BOO | 57.1 | 28.9 | 673 | 47.8 | 44 | 27 | 35 | 17 | 16 | 6 |
| NOR-366 | TRD | 54.3 | 38.1 | 321 | 44.3 | 40 | 13 | 30 | 18 | 23 | 16 |
| SWE-035 | 3 CI | 59.6 | 43.4 | 1491 | | | | | | | |
| SWI-053 | 3 CI | 63.1 | 44.7 | 3076 | | | | | | | |
| SWI-525 | ZRH | 54.0 | 44.7 | 1382 | 46.3 | 51 | | | | | |
| SWI-534 | ZRH | 53.6 | 45.1 | 1242 | 50.3 | 58 | | | | | |
| UKD-024 | LHR | 57.4 | 45.2 | 3845 | 48.2 | 55 | 10 | 28 | 23 | 20 | 19 |
| UKD-238 | GLA | 65.1 | 58.4 | 598 | 44.8 | 44 | 17 | 30 | 25 | 19 | 9 |
| UKD-242 | LGW | 60.1 | 35.7 | 537 | 45.1 | 48 | | | | | |
| | LHR | 62.5 | 54.6 | 1223 | 46.6 | 48 | | | | | |
| | LTN | 64.4 | 57.0 | 159 | 46.6 | 47 | | | | | |
| | MAN | 60.2 | 43.2 | 74 | 42.8 | 47 | | | | | |
| USA-022 | DEN | 59.1 | 30.5 | 670 | 42.4 | 33 | 6 | 25 | 19 | 19 | 31 |
| | DFW | 62.7 | 38.9 | 534 | 45.5 | 29 | 10 | 29 | 16 | 19 | 26 |
| | LAX | 66.0 | 51.2 | 475 | 42.2 | 33 | 7 | 26 | 18 | 22 | 27 |
| | ORD | 65.2 | 37.1 | 556 | 44.0 | 33 | 6 | 23 | 16 | 18 | 36 |
| USA-032 | BOS | 68.5 | 63.2 | 760 | 45.8 | 28 | 8 | 21 | 19 | 20 | 34 |
| | JFK | 69.9 | 66.3 | 333 | 44.0 | 28 | 3 | 17 | 19 | 22 | 40 |
| | MIA | 64.6 | 41.8 | 447 | 50.7 | 42 | 11 | 34 | 18 | 16 | 21 |
| USA-044 | CHA | 65.7 | 37.3 | 895 | 46.9 | 28 | 6 | 30 | 22 | 21 | 21 |
| | RNO | 64.3 | 38.6 | 717 | 43.9 | 30 | 6 | 24 | 21 | 22 | 27 |
| USA-082 | LAX | 62.5 | 44.7 | 374 | 47.4 | 41 | | | | | |
| USA-203 | BUR | 62.0 | 54.4 | 586 | 40.5 | 47 | | | | | |
| USA-204 | SNA | 62.6 | 49.6 | 601 | | | | | | | |
| USA-338 | 7MIL | 63.6 | 48.7 | 839 | | | | | | | |

(Continued)

| | | Use% | | | | Education% | | | | Occupation% | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Study ID | airport | not | low | use | high | 1st | 2nd | higher | uni | low | med | hi |
| AUL-210 | ADL | | | | | 19 | 68 | 5 | 8 | | | |
| | MLB | | | | | 12 | 79 | 4 | 5 | | | |
| | PER | | | | | 8 | 80 | 5 | 7 | | | |
| | RCM | | | | | 12 | 73 | 7 | 8 | | | |
| | SYD | | | | | 15 | 70 | 5 | 10 | | | |
| CAN-168 | YYZ | 20 | 31 | 28 | 21 | 44 | 41 | 0 | 15 | 8 | 56 | 37 |
| FRA-016 | 4 CI | | | | | | | | | | | |
| FRA-239 | ORY | | | | | | | | | 32 | 56 | 11 |
| GER-531 | FRA | 29 | 62 | 0 | 10 | 43 | 34 | 5 | 18 | 35 | 61 | 4 |
| NET-240 | AMS | | | | | 17 | 66 | 9 | 7 | 41 | 39 | 20 |
| NOR-311 | FBU | 27 | 33 | 0 | 40 | | | | | 21 | 19 | 60 |
| NOR-328 | BOO | | | | | 28 | 0 | 50 | 22 | | | |
| NOR-366 | TRD | | | | | 22 | 0 | 49 | 30 | | | |
| SWE-035 | 3 CI | | | | | | | | | | | |
| SWI-053 | 3 CI | | | | | | | | | | | |
| SWI-525 | ZRH | 18 | 59 | 0 | 16 | 6 | 15 | 60 | 19 | 27 | 64 | 9 |
| SWI-534 | ZRH | 30 | 52 | 0 | 12 | 4 | 13 | 60 | 24 | 39 | 60 | 1 |
| UKD-024 | LHR | 46 | 0 | 54 | 0 | | | | | 27 | 58 | 15 |
| UKD-238 | GLA | | | | | | | | | 31 | 63 | 6 |
| UKD-242 | LGW | | | | | | | | | 13 | 36 | 51 |
| | LHR | | | | | | | | | 13 | 29 | 57 |
| | LTN | | | | | | | | | 19 | 44 | 37 |
| | MAN | | | | | | | | | 23 | 41 | 36 |
| USA-022 | DEN | 51 | 0 | 49 | 0 | 30 | 37 | 22 | 12 | 14 | 30 | 56 |
| | DFW | 73 | 0 | 27 | 0 | 51 | 25 | 14 | 9 | 28 | 32 | 40 |
| | LAX | 51 | 0 | 49 | 0 | 30 | 37 | 23 | 11 | 16 | 30 | 53 |
| | ORD | 55 | 0 | 45 | 0 | 35 | 34 | 18 | 12 | 8 | 33 | 59 |
| USA-032 | BOS | 52 | 9 | 39 | 0 | 10 | 63 | 17 | 10 | 21 | 29 | 50 |
| | JFK | 38 | 10 | 52 | 0 | 9 | 56 | 17 | 18 | 16 | 15 | 70 |
| | MIA | 25 | 7 | 68 | 0 | 17 | 38 | 24 | 21 | 32 | 24 | 45 |
| USA-044 | CHA | 59 | 8 | 33 | 0 | 15 | 54 | 16 | 15 | 4 | 35 | 61 |
| | RNO | 36 | 10 | 53 | 0 | 13 | 54 | 22 | 12 | 9 | 39 | 51 |
| USA-082 | LAX | | | | | | | | | 19 | 30 | 50 |
| USA-203 | BUR | | | | | | | | | | | |
| USA-204 | SNA | | | | | | | | | | | |
| USA-338 | 7MIL | | | | | | | | | | | |

(Continued)

| | | Fear% | | | Sensitivity% | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Study ID | airport | low | med | hi | low | med | hi | Depend% | Own% |
| AUL-210 | ADL | 48 | 22 | 30 | | | | | 77 |
| | MLB | 43 | 15 | 42 | | | | | 88 |
| | PER | 62 | 13 | 25 | | | | | 77 |
| | RCM | 47 | 19 | 34 | | | | | 61 |
| | SYD | 38 | 18 | 44 | | | | | 73 |
| CAN-168 | YYZ | | | | 42 | 38 | 19 | 7 | 96 |
| FRA-016 | 4 CI | | | | | | | | |
| FRA-239 | ORY | 72 | 17 | 12 | | | | 8 | 71 |
| GER-531 | FRA | 64 | 18 | 18 | 48 | 33 | 19 | 6 | 60 |
| NET-240 | AMS | | | | | | | 9 | 46 |
| NOR-311 | FBU | 57 | 37 | 6 | | | | 4 | 79 |
| NOR-328 | BOO | | | | | | | 5 | |
| NOR-366 | TRD | | | | | | | 5 | |
| SWE-035 | 3 CI | | | | | | | | |
| SWI-053 | 3 CI | | | | | | | | |
| SWI-525 | ZRH | | | | 43 | 37 | 19 | | 49 |
| SWI-534 | ZRH | | | | 43 | 40 | 17 | | 56 |
| UKD-024 | LHR | 62 | 34 | 4 | | | | 7 | 48 |
| UKD-238 | GLA | 62 | 22 | 16 | | | | 1 | 19 |
| UKD-242 | LGW | | | | 32 | 52 | 16 | 18 | |
| | LHR | | | | 34 | 46 | 20 | 7 | |
| | LTN | | | | 35 | 47 | 18 | 4 | |
| | MAN | | | | 26 | 58 | 16 | 1 | |
| USA-022 | DEN | 81 | 8 | 11 | | | | 8 | 73 |
| | DFW | 76 | 9 | 14 | | | | 9 | 58 |
| | LAX | 65 | 14 | 21 | | | | 11 | 68 |
| | ORD | 84 | 7 | 9 | | | | 7 | 70 |
| USA-032 | BOS | 58 | 16 | 26 | | | | 8 | 66 |
| | JFK | 56 | 13 | 31 | | | | 7 | 89 |
| | MIA | 83 | 11 | 6 | | | | 14 | 74 |
| USA-044 | CHA | 69 | 15 | 16 | | | | 2 | 82 |
| | RNO | 81 | 10 | 9 | | | | 7 | 78 |
| USA-082 | LAX | 58 | 0 | 42 | | | | | |
| USA-203 | BUR | | | | | | | | |
| USA-204 | SNA | | | | | | | | |
| USA-338 | 7MIL | | | | | | | | |

## 4.5 The influence of covariates in the model: results

*Gender of respondent*
Table 4 shows that men and women react in a similar way to aircraft noise. The overrepresentation of women in the studies (overall, 55.9% is female) may be related to the fact that women probably were at home more often at the time of interviewing. Consequently, the outcome indicates indirectly that annoyance is not higher if more time is spent at home.

*Age*
Table 4 shows that age has an effect on annoyance. The results indicate that the effect of age depends on the noise level: relatively young and relatively old persons are less annoyed. This is in line with our findings in earlier analyses that there is no linear relationship, but the relationship has a curvilinear shape. Note however that ages 40-70 yrs did not differ significantly from the reference category 30-40 yrs.

*Education level*
Information about education level was translated into categories based upon the International Standard Classification of Education (ISCED). The ISCED defines levels of education uniformly across all countries participating in the United Nations Educational, Scientific, and Cultural Organization The original ISCED categories were combined into four broader classes because often, available information was not a sufficient basis for a finer distinction. The definition of education levels in terms of the ISCED categories (4 does not exist) is as follows:

1. 1st =ISCED 0, 1 : completed primary school;
2. 2nd =ISCED 2, 3 : completed secondary school, high school;
3. High =ISCED 5 : completed higher education not leading to a first university degree;
4. University =ISCED 6, 7 : (polytechnics) university, first degree and postgraduate level.

Results for education level are in Table 4. The category ‘High’ did not differ significantly from the reference level ‘2nd level.

*Occupational status*
The available information about occupation and occupational status is very diverse. Categories were combined and sometimes ordered to create classes ordered according to occupational status. For example, in study NOR-311 there was a classification of blue collar workers (1) unskilled and (3) skilled and a classification of white collar workers (2) general office worker, (4) professional worker, and (5)manager The numbers indicate the rank order used with this information. Such a rank order is not self-evident and involves a subjective judgment. If occupational status was determined for more than one member of the household, then the highest level was taken. Respondents without occupation (student, homemaker, retired, etc.) were excluded from the analysis, except when there was information about the occupation of another member of the household (breadwinner).The number of categories was not equal for all studies. In order to obtain a comparable indicator for occupational status, the categories were translated into a 0–100 scale in the same manner as described above for annoyance. In the present analysis, this scale is divided into three levels: low (0–32), medium (33–66), and high (67–100). The results in Table 4 indicate that the reaction to aircraft noise is not strongly related to occupational status, only the category ‘Low’ differed slightly from the category ‘Medium’. Education and occupational status are two components of socioeconomic status. In general, the classification of the education will be more accurate and unambiguous.

*Number of persons in household*
Results from Table 4 indicate that noise annoyance has a weak relation with the size of the household. Single persons tend to be less annoyed by noise, and persons in a household with two persons tend to be more annoyed by noise.

*Homeownership*
The results from Table 4 confirm that homeowners are more concerned about environmental noise as can be expected.

*Dependency on the noise source*
Respondents who depend economically on aircraft related activities are expected to report less annoyance than persons who have no economic relation with that activity. Many aircraft noise surveys included a question about this kind of dependency. An example of a question about economic dependency is ‘‘Are you or anyone else in the family employed at this time by the airport or by an airline company?’’ with, for example, the following response categories: ‘‘yes’’ and ‘‘no.’’ Table 4 shows that noise annoyance is related to economic dependency, and gives estimates of the effect of dependency.

*Use of airplane travel*
Respondents who frequently travel by air are expected to report less annoyance than persons who do not. An example of a question about the use of air travel is: ‘‘Looking back at the last 12 months, how many times have you flown?’’ with, for example, the following response categories: ‘‘10 or more,’’ ‘‘4–9,’’ ‘‘more seldom,’’ ‘‘never.’’ The responses are classified into a four categories: not, low, use, and high. Table 4 gives estimates of the effect of this variable.

*Noise sensitivity*
Respondents who report to be sensitive to noise are expected to be more annoyed at the same exposure level. In various studies, a question such as ‘‘Are you sensitive to noise?’’ is included with, for example, the following response categories: ‘‘more than average,’’ ‘‘about average,’’ and ‘‘less than average.’’ In order to obtain a comparable indicator for noise sensitivity, the categories were translated to a 0–100 scale in the same manner as described above for annoyance. In the present analysis, this scale is divided into three levels: low (0–32), medium (33–66), and high (67– 100). The results in Table 4 show that noise sensitivity has the expected effect: respondents who report to be not sensitive to noise report less annoyance than highly sensitive respondents.

*Fear*
Respondents who express fear associated with aircraft noise are expected to be more annoyed at the same exposure level. Fear with respect to aircraft noise is determined with a question such as ‘‘When you see or hear planes overhead, how often do you feel there is some danger that they might crash nearby?’’ with, for example, the following response categories: ‘‘never,’’ ‘‘sometimes,’’ ‘‘often,’’ and ‘‘very often.’’ In order to obtain a comparable indicator, again the categories were translated into a 0–100 scale in the same manner as described above for annoyance. In the present analysis, this scale is divided into three levels: low (0–32), medium (33–66), and high (67–100). Table 4 shows that fear is related to noise annoyance in the expected way. At the same exposure level, persons with fear concerning airplanes are more annoyed than persons without such feelings. The effects for fear estimated are given in Table 4. It should be mentioned, however, that the effect of fear on annoyance may have been overestimated because of two reasons. One reason is the routing in some of the questionnaires used in the aircraft studies. In these studies, persons who did not notice the aircraft skipped the fear question and were assumed to experience no fear of

the aircraft. While this appears to be a reasonable assumption, the correlation between fear and noise annoyance may also partly be attributed to the correlation between fear and noise exposure, with higher exposure levels inducing more fear in respondents, as well as more annoyance.

*Year of study*
In earlier studies a significant increase over the years in expected annoyance at a given level of aircraft noise exposure was found (Janssen et al., 2011). Instead of a gradual increase, annoyance appeared to show an increase from around 1996 onward. To quantify this increase we included a dummy variable contrasting the studies from before 1996 with the ones done in 1996 and later. Because not all of the studies used in the earlier analysis are available in the present analysis this dummy variable effectively contrasts aircraft studies from 1992 and earlier with studies from 2001 and onward. Given the large difference in annoyance, the justifiability of pooling recent and earlier studies into one single relationship may be questioned. Although this is done in the present analysis (see 4.6), this is only done for the purpose of a comparison with the method adopted by the ISO Working Group 45, and should not be viewed as an updated dose-response relationship.

*Summary of demographical, attitudinal and study characteristics*.
Fear has a very large impact on annoyance. Persons who experience fear related to aircraft report higher annoyance compared to persons who do not experience such fear. With three categories, the difference between the lowest and the highest fear level is equivalent to an average DNL difference 22.5 dB. Another important factor is noise sensitivity. With three categories, the difference in annoyance between the nonsensitive and highly sensitive persons is equivalent to an average DNL difference of 10.8 dB.
The findings are consistent with the hypotheses that higher annoyance is reported if the education is higher, the occupational status is higher, the dwelling is owned instead of rented, if a person does not depend on the noise source, and if the use of airplane travel is low. In addition, a person in a household consisting of two persons reports more annoyance than a person in a household of another size. However, the effects of these factors on noise annoyance are small, i.e., the average equivalent DNL difference is equal to 0–3 dB, and, in the case of homeownership, 4.2 dB. Respondents in studies conducted recently have higher annoyance than studies conducted longer ago. Results found in the present analysis are consistent with earlier findings (Miedema and Vos, 1999, Janssen et al., 2011).

**Table 4:** Differences in annoyance (*DNL* equivalent), the significance of the difference compared to the reference category, and the range of *DNL* differences for different categories of the same variable

| Variable | Categories | *DNL* equivalent (average) | significant ($p < 0.05$) | Range of *DNL* differences |
|---|---|---|---|---|
| Gender | | - | | 0 |
| Age | <20 | -6.8 | * | |
| | 20-30 | -2.4 | * | |
| | 30-40 | 0 | | |
| | 40-50 | -0.2 | | 7 |
| | 50-60 | -0.3 | | |
| | 60-70 | 0.7 | | |
| | 70+ | -2.2 | * | |
| Education | 1st | -1.3 | * | |
| | 2nd | 0 | | |
| | High | 0.4 | | 3 |
| | Univ | 1.9 | * | |
| Occupation | Low | -1.0 | * | |
| | Medium | 0.0 | | 1 |
| | High | 0.3 | | |
| Household size | 1.0 | 2.3 | * | |
| | 2.0 | 0 | | |
| | 3.0 | 2.2 | | 2 |
| | 4.0 | 1.5 | | |
| | >=5 | 1.0 | * | |
| Homeownership | Renter | 0 | | 4 |
| | Owner | 4.2 | * | |
| Dependency | Depend | 0 | | |
| | Not depend | -3.4 | * | 3 |
| Use | Not | 0 | | |
| | Low | -0.6 | | |
| | Use | -1.2 | * | 3 |
| | High | -2.8 | * | |
| Sensitivity | Low | 0 | | |
| | Medium | 8.3 | * | 11 |
| | High | 10.8 | * | |
| Fear | Low | 0 | | |
| | Medium | 12.2 | * | 23 |
| | High | 22.6 | * | |
| Year of study | Before 1996 | 0 | | 8 |
| | 1996 and later | 8.2 | * | |

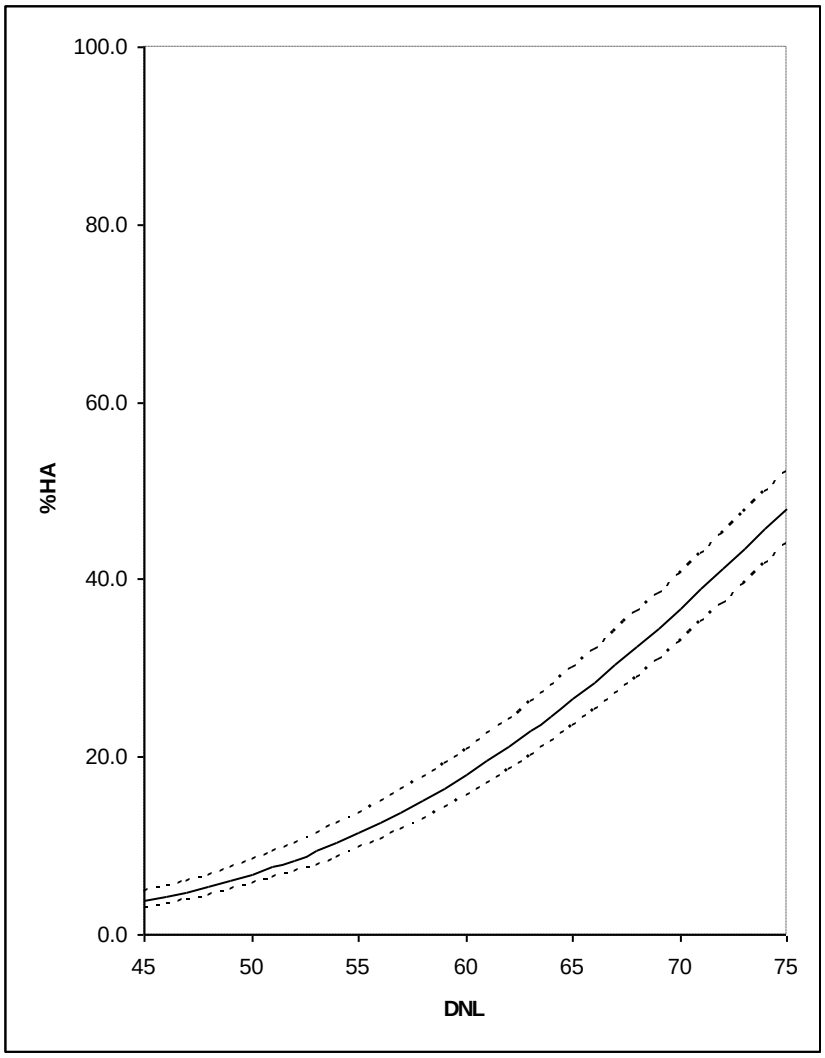
## 4.6 Dose-response relationship for comparison between methods

The estimates for the dose-response model based on the data available for this analysis are given in Table 5, and the resulting relationship between *DNL* and *%HA* is given in Figure 3.

**Table 5:** Dose-response relationship parameter estimates

| | EST | SE | Z | P |
|---|---|---|---|---|
| (Intercept) | -75.1 | 2.7 | -27.5 | 0 |
| LDN | 1.9 | 0.0 | 57.1 | 0 |
| $\sigma^2_0$ | 104.0 | | | |
| $\sigma^2_1$ | 1030.4 | | | |

**Figure 3:** Percentage highly annoyed estimated from *DNL* and 95% confidence intervals




| *DNL* | *%HA* |
|---|---|
| 45 | 3.8 |
| 46 | 4.2 |
| 47 | 4.8 |
| 48 | 5.4 |
| 49 | 6.1 |
| 50 | 6.8 |
| 51 | 7.6 |
| 52 | 8.4 |
| 53 | 9.4 |
| 54 | 10.4 |
| 55 | 11.4 |
| 56 | 12.6 |
| 57 | 13.8 |
| 58 | 15.1 |
| 59 | 16.5 |
| 60 | 18.0 |
| 61 | 19.5 |
| 62 | 21.2 |
| 63 | 22.9 |
| 64 | 24.6 |
| 65 | 26.5 |
| 66 | 28.4 |
| 67 | 30.4 |
| 68 | 32.5 |
| 69 | 34.5 |
| 70 | 36.7 |
| 71 | 38.9 |
| 72 | 41.1 |
| 73 | 43.4 |
| 74 | 45.6 |
| 75 | 47.9 |

# 5 Comparison between methods

The relationship between *DNL* and aircraft noise annoyance presented in Chapter 4 is based on an analysis on the overlapping part of the datasets of TNO and the ISO Working Group 45. This was done in order to be able to compare the outcomes of the TNO-approach to the approach of the ISO Working Group (hereafter named the CTL-approach, referring to the introduction of a factor called the Community Tolerance Level (see Fidell & Mestre, 2010) regarding the expected percentages of high annoyance at a given exposure level in DNL. In Figure 4, the curve derived by the TNO-approach is compared to the curve derived by the CTL-approach based on the same dataset. Given the large uncertainties in the prediction of the community response found in a particular survey, the curves do not deviate much from each other. However, the CTL-curve gives lower estimates for the annoyance response at exposure levels below 55 dB(A) than the TNO-curve, which, because of the high number of people exposed to these levels, may lead to important differences in the estimated number of (highly) annoyed people in for instance health impact assessments.

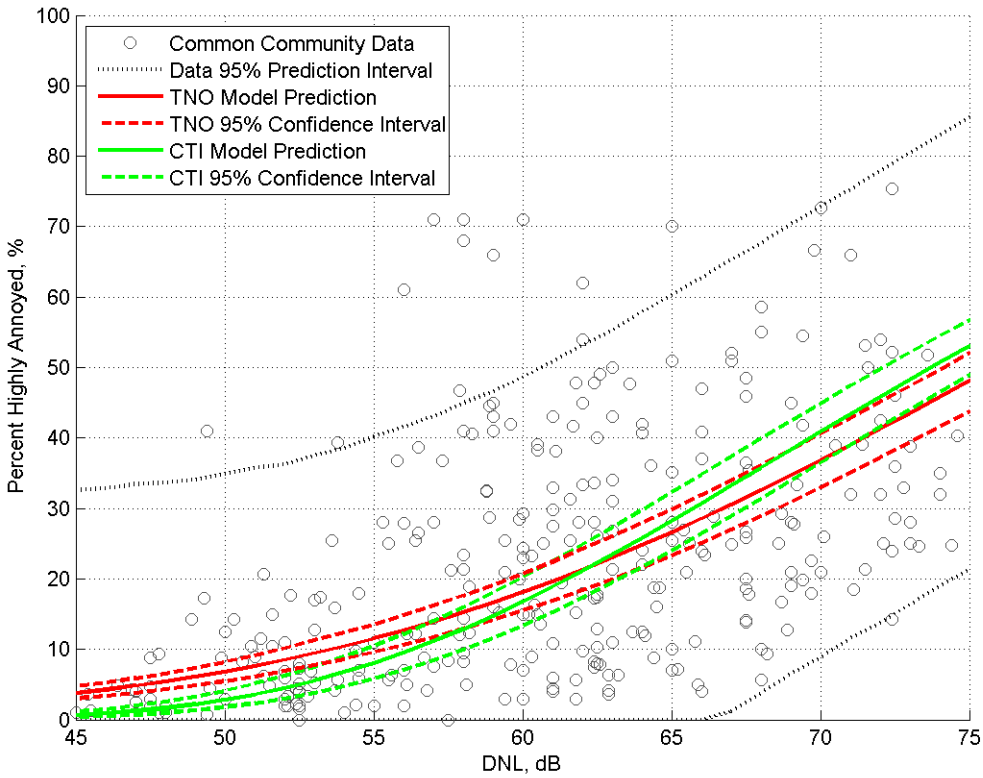



**Figure 4:** Comparison between dose-response relationships derived by the TNO-approach and the CTL-approach, including 95% confidence intervals and the 95% prediction interval based on the aggregated data (done by Aaron Hastings of the FAA).

However, more important than the similarities between the models or their deviations from each other is how each approach deals with the underlying data, the assumptions made, how statistical uncertainties are handled, and how the model may be used in policy. The methods are compared on the basis of these aspects, after which the strengths and weaknesses of both methods are discussed.

## 5.1 Underlying data

A large difference between the approaches lies in the way in which the underlying data are prepared. The CTL-approach uses aggregated data, i.e. the percentages of highly annoyed respondents per exposure category for each study, if available also per site. The level of analysis is the study or site level, where each study or site and each exposure category within study or site is given equal weight. High annoyance is determined either by a cutoff point depending on the category label 'highly annoyed' or similar wording, or alternatively by a certain cutoff score in the case of a numerical scale. Few criteria are used for the selection of studies, allowing as many datasets as possible to be included in the analyses.

In the TNO-approach the model is based on individual dose and response data, with the respondent level being the level of analysis. This means that every respondent is weighted equally, and large studies have more weight than smaller studies. Furthermore, extreme exposure levels (*DNL* < 45 or > 75 dB) are excluded, because the risk of unreliable data is high at very low levels, whereas the risk of self-selection of people that are not affected by noise is high at very high levels. Other criteria that are used for selection of appropriate data are that the dose and the annoyance response are source-specific (i.e. that they pertain to the same noise source), and that annoyance can be derived from one general noise question, and not from an index constructed of several specific disturbances. The various annoyance scales used in the different studies are all recoded into a 0-100-point score to make them comparable between studies and to be able to use a consistent cutoff point between studies. While these cutoff points are used to calculate the *%A* or *%HA* from the model, the whole annoyance distribution is modeled as a function of the noise exposure.

*Strengths and weaknesses*
An advantage of using aggregated data, like in the CTL-approach, is that they will be easier to achieve than information on individual dose and response data, and therefore the potential number of studies on which a relationship may be based will be higher. A weakness of the CTL-approach is that equal weights are given to the data points, despite different numbers of observations per noise category, per site and per study. As a result, coincidentally very high or very low values based on only few data points may have a disproportionate influence on the outcome. This means for instance that the CTL score for a particular study may be sensitive to the chosen size of the exposure categories, or that the CTL score of a small survey with large variance and uncertainty will have equal influence on the dose-response curve as a large survey based on much more information. It may be argued that weighing every respondent equally, like in the TNO-approach, will result in more influence of airports near large communities, where large studies are usually done, on the outcome of the dose-response modeling. From a statistical point of view this is correct, however, and from a policy view it may also be defended.
An advantage of the TNO-approach is that it makes maximum use of the information in the dataset by basing the model on individual dose and response data. Recoding the annoyance scales into a 0-100 point score makes the scales comparable between studies and enables modeling the whole distribution of the annoyance scale, as opposed to high versus lower annoyance, as a function of noise exposure. However, it requires the assumption that categories on an annoyance scale are evenly distributed across this virtual 100-point scale, which may not always be justified.

## 5.2 Assumptions regarding the relationship between DNL and annoyance

The approaches also differ in their assumptions regarding the relationship between *DNL* and annoyance. The CTL-approach involves a normative approach, assuming that *%HA* follows the duration-corrected ("effective") loudness estimated from *DNL* values. This is assumed to represent the response to the acoustic properties of the noise, whereas deviations from this are attributed to either non-acoustic factors or residual measurement errors. Equal shapes of the relation between *DNL* and annoyance are assumed across studies or noise sources. Differences in annoyance response between studies or subsets of studies are expressed in the Community Tolerance Level (CTL), defined as the *DNL* level at which 50% of the people are highly annoyed in a given study or community.

In contrast, in the TNO-approach the model is based on a statistical fit to the underlying data, modeling the distribution of annoyance responses as a function of the noise exposure. The statistical model assumes that the dependent variable (the annoyance score) is randomly distributed with the mean of the distribution being a function (linear combination) of predictor variables (i.e. *DNL*, with the option of adding other predictor variables of interest). It should be noted, however, that since annoyance is assumed to have a censored normal distribution, the expected annoyance score estimated from the model will depend nonlinearly on the exposure level and other predictors. Subsequently, the probability of exceeding any chosen cutoff point (such as 72 for being *HA*) at a given *DNL* may be derived from the mean and the variance of the distribution.

*Strengths and weaknesses*
The possibility of distinguishing acoustic and non-acoustic influences on annoyance is an appealing aspect of the CTL-approach. However, it is not tested how the assumed relationship between *DNL* and *%HA* relates to the best fit to the data or whether it leads to improved explanation of variance compared to other assumptions. This is not trivial, since the issue of whether loudness represents the "acoustic" part of annoyance is not resolved yet. Furthermore, assuming equal shapes of the relation between *DNL* and annoyance across studies does not allow testing for potential differences in the slope of curves, for instance between different noise sources, or between recent and earlier studies.
A disadvantage of the TNO-approach is that the different steps involved in the model may be difficult to grasp instantly, the method being statistically sophisticated. However, the results are readily interpretable, giving information on both the effect of *DNL* and the effect of several non-acoustic variables on annoyance.

## 5.3 Statistical handling of uncertainties based on variance within and between studies

The approaches also differ in the way they deal with variance, both within studies and between studies. In the CTL-approach, because of the use of aggregated data, the observed individual variance in the annoyance response within studies or sites and within noise categories is not taken into account. For the characterization of the between-study variance, the CTL (Community Tolerance Level) is adopted, which is the *DNL* level at which 50% of the people are highly annoyed in a given study or community. Together, the CTL and the loudness function are found to account for on average two-thirds of the variance in the association of observed and predicted prevalence rates per study. Using the CTL, differences in annoyance between studies or communities may be expressed in terms of equivalent exposure levels. Also, confidence intervals for the prediction of annoyance may be based on

the distribution of CTL values, and differences in mean CTL values among subsets of study findings may be tested.

In the TNO-approach, the between-study variance is distinguished from the individual variance by including a random study (or airport within study) effect in the statistical model. This is necessary because the respondents in the dataset are not drawn at random, but can be thought of as having been drawn in clusters defined by the (airports within) studies. If properly established, the confidence interval to describe the accuracy of the estimation of the relationship takes into account the variation between individuals as well as the variation between studies. As found by Miedema & Oudshoorn (2001), this results in relatively narrow confidence intervals (as opposed to the wide prediction intervals for individuals or groups). In addition to establishing a dose-response relationship and its confidence intervals, it is worthwhile to be able to explain the large variance between and within studies. The TNO-approach allows for investigating the influence of both study characteristics and individual characteristics on annoyance, either by including additional predictor variables in the model, or by assessing the relation between study characteristics and the study-specific intercept in the model. In this way, the influence of a range of variables can be quantified in dB equivalents.

*Strengths and weaknesses*
Because of the use of aggregated data in the CTL-approach, the observed individual variance in the annoyance response within studies or sites and within noise categories is not taken into account. This may lead to various types of biases and is statistically doubtful.
Still, a very attractive feature of the CTL is that differences in annoyance between communities may be expressed in terms of equivalent exposure levels. Together, the CTL and the loudness function are found to account for on average two-thirds of the variance in the association of observed and predicted prevalence rates per study. However, it should be kept in mind that the predictive value of the CTL is irrelevant, as long as we do not know whether this variable reflects population differences, study characteristics, response bias, source characteristics or exposure or response assessment errors. The goal should be to improve the prediction of annoyance, which can only be achieved by gaining information on the variables that cause the variability in annoyance. One of the ways to do this is by assessing their influence on CTL scores, but another way of doing this is by directly assessing their influence on annoyance as is done in the TNO-approach.

## 5.4 Use of the model in policy

The CTL-approach may appeal more to policy makers than the more complex statistical TNO-method. However, it is not clear how exactly it would be used in policy. The CTL in itself is not an explanatory variable, and its predictive value is not very useful as long as we need a survey to establish the CTL of a certain community. Also, the term Community Tolerance Level strongly suggests that it only reflects differences in tolerance between specific populations, while it may also reflect study characteristics, response bias, source characteristics and systematic exposure or response assessment errors. Furthermore, the distinction made between community tolerance and loudness-related annoyance may suggest to policy makers that they only have to deal with the “objective” annoyance that is related to loudness, which would not do justice to the highly subjective character of annoyance. Of course, it would be interesting if it becomes possible to estimate the CTL on the basis of certain characteristics, allowing a better prediction of the annoyance in a specific community. However, would that mean that policy makers should for instance install different limit values depending on the “sensitivity” of the community? In most cases, the uncertainty regarding

individual or group reactions is not what matters for noise policy. Most policy decisions are made with a view to the overall reaction to exposures in a (reference) population. This means that it is not the uncertainty with respect to the prediction of an individual or group reaction that is important, but the uncertainty regarding the exact relationship between exposure and response in the (reference) population. The best way to estimate this would be by a statistical method that takes into account both the individual and the study variance. On the other hand, it is very informative to be able to explain why certain communities may show a higher annoyance response than others, in order to be able to prevent or adequately respond to the situation. Information on these aspects may be gained from both methods, although the TNO-approach has the advantage that in addition to characteristics at the study level, also the influence of individual variables may be assessed.

# 6 References

Alexandre, A. (1970). Prévision De La Gêne Due Autour Des Aéroports Et Perspectives Sur Les Moyens D'y Remédier. (Prediction of Annoyance Due to Noise Around Airports and Speculations on the Means for Controlling It). Doc. A.A. 28/70, pp. 1-151.

Babisch, W., Houthuijs, D., Pershagen, G., Cadum, E., Katsouyanni, K., Velonakis, M., Dudley, M.L., Marohn, H.D., Swart, W., Breugelmans, O., Bluhm, G., Selander, J., Vigna-Taglianti, F., Pisani, S., Haralabidis, A., Dimakopoulou, K., Zachos, I., Jarup, L. and HYENA Consortium (2009). Annoyance due to aircraft noise has increased over the years- results of the HYENA study. Environ. Int. 35, pp. 1169-1176.

Borsky, P.N. (1983). Integration of Multiple Aircraft Noise Exposures Over Time by Residents Living Near U.S. Air Force Bases. Noise as a Public Health Problem (Fourth International Congress), pp. 1049-1060, Centro Ricerche e Studi Amplifon, Milano, Italy.

Brink, M., Wirth, K., Schierz, C., Thomann, G., and Bauer, G. (2008). Annoyance Responses to Stable and Changing Aircraft Noise Exposure. J.Acoust.Soc.Am., 5, vol. 124, pp. 2930-2941.

Brooker, P.; and Richmond, C. (1985). The United Kingdom Aircraft Noise Index Study: Part I -- Main Results. Institute of Acoustics, April 1985 (York), pp. 323-329.

Bugge, J.J., Gjestland, T., Liasjø, K.H., and Granøien, I.L.N. (1991). Preliminary Results From a Study of Community Response to Noise From Military Aircraft Exercise. Internoise 91, pp. 203-206.

Bullen, R.B., and Hede, A.J. (1986). Comparison of the Effectiveness of Measures of Aircraft Noise Exposure by Using Social Survey Data. J. Sound Vib., 2, vol. 108, pp. 227-245.

Diamond, I.D., and Walker, J.G. (1986). An International Study of the Influence of Residual Noise on Community Disturbance to Aircraft Noise. Inter-noise 86, pp. 941-946.

Fidell, S.A., and Jones, G. (1975). Effects of Cessation of Late Night Flights on an Airport Community. J. Sound Vib.4, vol. 42, pp. 441-427.

Fidell, S.A., Mills, J. Teffeteller, S.R. and Pearsons, K.S. (1982). Community Response to Three Noise Abatement Departure Procedures at John Wayne Airport.BBN Rep. 4743. Bolt Beranek and Newman, Canoga Park, California.

Fidell, S., Barber, D. S., and Schulz, Th. J. (1991). Updating as dosage-effect relationship for the prevalence of annoyance due to general transportation noise. J.Acoust.Soc.Am. 89, pp. 221-233.

Fidell, S. and Mestre, V. (2010). Recommendation for predicting the prevalence of Annoyance with transportation noise. Memorandum to the ISO Working Group 45, May 2010, Lisbon (Portugal).

Gerven, P.W.M. van, Vos, H., Boxtel, M.P.J. van, Janssen, S.A., and Miedema, H.M.E. (2009). Annoyance from environmental noise across the lifespan, J. Acoust. Soc. Am. 126, pp. 187-194.

Gjestland, T., Liasjø, K.H., Granøien, I.L.N., Bøhn, H.E. and Gaustad, A. (1990). A Noise Survey Around Oslo Airport Fornebu. Internoise 90, pp. 451-454.

Gjestland, T., Granøien, I.L.N., Liasjø, K.H., and Bugge, J.J. (1993). Community Response to Noise From a Short Term Military Aircraft Exercise. Noise and Man '93: Noise as a Public Health Problem (Sixth International Congress), vol. 2, pp. 589-592, INRETS, Arcueil, France.

Graf, P., Meier, H.P., and Müller, R. (1974). SozioPsychologische Fluglärmuntersuchung Im Gebiet Der Drei Schweizer Flughäfen, Zürich, Genf, Basel. (Translation Available in:

Sociopsychological Airplane Noise Investigation in the Districts of Three Swiss Airports: Zurich, Geneva, and Basel. NASA TM-75787).

Groothuis-Oudshoorn, C.G.M., and Miedema, H.M.E. (2006). Multilevel Grouped Regression for Analyzing Self-reported Health in Relation to Environmental Factors: the Model and its Application, Biom. J. 48, pp. 67-82.

Guski, R. (2004). How to Forecast Community Annoyance in Planning Noisy Facilities, Noise Health 6, pp. 59-64.

Hall, F.L., Birnie S.E., Taylor, S.M., and Palmer, J.E. (1981). Direct Comparison of Community Response to Road Traffic Noise and to Aircraft Noise. J.Acoust.Soc.Am. 6, vol. 70, pp. 1690-1698.

Hazard, W.R. (1971). Predictions of Noise Disturbance Near Large Airports. J. Sound Vib., 4, vol. 15, pp. 425-445.

Janssen, S.A. and Vos, H. (2009). A comparison of recent surveys to aircraft noise exposure-response relationships. Report No. TNO-034-DTM-2009-01799. TNO, Delft, 2009.

Janssen, S.A. and Vos, H., Kempen, E.E.M.M. van, Breugelmans, O.R.P., Miedema, H.M. E. (2011). Trends in aircraft noise annoyance: the role of study and sample characteristics. J. Acoust. Soc. Am. (in press).

Kempen, E.E.M.M. van, and van Kamp, I. (2005). Annoyance from air traffic noise: Possible trends in exposure-response relationships, National Institute of Public Health and the Environment, Bilthoven, the Netherlands. Report 01/2005 MGO EvK, reference 00265/2005.

Knowler, A.E. (1971). The Second Noise and Social Survey Around Heathrow, London Airport. 7th International Congress on Acoustics, Budapest, vol. 2, August 18-26, 1971, pp. 525-528.

Kryter, K.D. (1982). Community annoyance from aircraft and ground vehicle noise, J. Acoust. Soc. Am. 72, pp. 1212-1242.

Kryter, K. D. (1983). Response of K.D. Kryter to modified comments by Th.J. Schultz on K.D. Kryter's paper “Community annoyance from aircraft and ground traffic noise". J.Acoust.Soc.Am. 73, pp. 1066-1068.

Miedema, H.M.E. and Vos H. (1998). Exposure-response relationships for transportation noise. J. Acoust.Soc. Am. 104, pp. 3432-3445.

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

Miedema H.M.E., Vos, H., de Jong, R.G. (2000). Community reaction to aircraft noise: time-of-day penalty and tradeoff between levels of overflights. J.Acoust.Soc.Am. 107, pp. 3245-3253.

Miedema, H. M. E. and Oudshoorn, C. G. M. (2001). Annoyance from Transportation Noise: Relationships with Exposure Metrics *DNL* and *DENL* and Their Confidence Intervals. Environmental Health 109, pp. 409-416.

Miedema, H.M.E. and Vos, H. (2003.) Noise sensitivity and reactions to noise and other environmental conditions. J.Acoust.Soc.Am. 113, pp. 1492-1504.

Patterson, H.P. and Connor, W.K. (1973). Community Responses to Aircraft Noise in Large and Small Cities in the U.S.A. International Congress on Noise as a Public Health Problem, Dubrovnik, Yugoslavia, May 13-18.

Rylander,R., Sörensen,S., and Kajland,A. (1972). Annoyance Reactions From Aircraft Noise Exposure. J. Sound Vib., 4, vol. 24, pp. 419-444.

Raw, G.J. and Griffiths, I.D. (1985). The Effect of Changes in Aircraft Noise Exposure. J. Sound Vib., 2, vol. 101, pp.273-275.

Schreckenberg, D., Meis, M., Kahl, C., Peschel, C and Eikmann, T. (2010). Aircraft noise and quality of life around Frankfurt Airport. Int J Environ Res Public Health. Sep; 7(9) pp. 3382-405.

Schultz, T. H. J. Synthesis of social surveys on noise annoyance. J. Acoust. Soc. Am.; Vol 64, 1978, pp. 377-405.

Vallet, M., Pachiaudi, G., Bruyere, J., Signolles, C., Tanguy, Y., Depitre, A., Fischl, M., Francois, J. and Abramowitch, J.M. (1986). Réactions De La Communaute Au Bruit Des Avions. (Translation Available in: Reactions of the Community to Aircraft Noise. NASA TT-20513). INRETS-Laboratoire Energie Nuisances, Bron, France.

# 7 Authentication

Name and address of the principal
Federal Aviation Administration (FAA), *contract through:*
Volpe National Transportation Systems Centre
55 Broadway VP-32
CAMBRIDGE MA 02142-1001

Names and functions of the co-operators
Dr. S.A. (Sabine) Janssen – senior scientist
H. (Henk) Vos – scientist/statistical data manager

Date upon which, or period in which the research took place
April 2010 – January 2011

Name and signature reviewer:

H.C. Borst, MSc.
Research Manager

Signature:

Dr. S.A. Janssen
Project leader

Release:

H.C. Borst, MSc.
Research Manager