European Commission

# Position paper on dose response relationships between transportation noise and annoyance

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EU's FUTURE NOISE POLICY, WG2 – Dose/Effect

# POSITION PAPER ON DOSE RESPONSE RELATIONSHIPS BETWEEN TRANSPORTATION NOISE AND ANNOYANCE

20 February 2002

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## Advisory note from the European Commission Services

*This position paper was prepared by a working group of noise experts set up by the European Commission in order to provide guidance on the dose-effect relations to be used for the assessment of numbers of people annoyed by noise.*

*This position paper was presented and discussed at three meetings of the Noise Steering Group, which comprises representatives of Member States, NGOs and industry. It should not be considered as an official statement of the position of the European Commission. Not all members of the Noise Steering Group necessarily share the views on every detail expressed in this document.*

*The European Commission and the French Ministry of the Environment made a financial contribution towards the expenses of the Working Group.*

# I - Introduction

Working Group 2 Dose/Effect was formed in 1998 by the European Commission with the following scope: *The WG shall support the European Commission with the development of the dose-effect relations for the proposed framework directive on the Assessment and Management of Environmental Noise.*

The present Position Paper[1] is one in a series on different topics within that scope that will be produced by the working groups assisting the European Commission in the coming years.

After a series of meetings, one of the members of the WG, Dr Henk Miedema of TNO in the Netherlands, was contracted by the Commission to develop the elements of a Position Paper on relationships between transportation noise and annoyance. This work was completed in August 2000 and the contents of the TNO report are reproduced in Annex I as a part of this Position Paper. The report describes in detail the process by which the results of a large number of studies and surveys were analysed to develop synthesised dose-response curves which can be used to estimate the number of annoyed persons or highly annoyed persons, given the noise exposure of their dwellings.

The present Position Paper summarises the recommended descriptors of noise exposure and of annoyance and recommends dose-effect curves, together with formulae. These curves are recommended for use in the context of the proposal for a Directive on the Assessment and Management of Environmental Noise[2].

Annex I of this document consists of the TNO report. Annex II of this document gives a concise overview of the meetings in which (parts of) the Position Paper were discussed and gives a list of the members of WG2.

# II - DESCRIPTORS

## 2.1. Noise exposure

Lden is defined in terms of the "average" levels during daytime, evening, and night-time, and applies a 5 dB penalty to noise in the evening and a 10 dB penalty to noise in the night. The definition is as follows:

$$\text{Lden} = 10 \lg [(12/24).10^{LD/10} + (4/24).10^{(LE+5)/10} + (8/24).10^{(LN+10)/10}]$$

Here LD, LE, and LN are the A-weighted long term $L_{Aeq}$ as defined in ISO 1996-2 (1987) for the day (7-19h), evening (19-23h), and night (23-7h) determined over the year at the most exposed facade. Lden has been put forward as the noise metric for the prediction of annoyance in the proposal for a Directive on the Assessment and Management of Environmental Noise.

[1] This document generally represents a consensus by the members of the Working Group. Not all experts necessarily share the views on every detail expressed in this document. It should not be considered as an official statement of the position of the European Commission. The European Commission and the French Ministry of the Environment made a financial contribution towards the expenses of the Working Group.

[2] COM (2000) 468 final, 2000-07-27.

## 2.2. Annoyance

This Position Paper recommends that the percentage of persons annoyed [%A], or the percentage of persons highly annoyed [%HA] be used as the descriptor of noise annoyance in a population. These descriptors of annoyance are derived from transforming various annoyance scales to a 0 to 100 basis and using a cut-off at the scale value 50 (for %A) or 72 (for %HA), respectively. Although this Position Paper does not make a final choice with respect to the annoyance descriptor, the selection of a single annoyance descriptor is recommended with a view to comparability.

Initially, %A has been chosen by WG2 instead of the more widely used %HA, because %A is more sensitive to changes in annoyance (between 50 and 72) at lower noise exposure levels. Most comments on the draft version of this Position Paper that proposed %A as the descriptor of annoyance, pertained to this choice of the annoyance descriptor. Moreover, additional experience has been obtained with the application of annoyance descriptors in quantifying annoyance on the basis of noise maps. The Working group has not and will not convene to make a definite proposal taking into account the comments and the additional experience. The following brief discussion is given in order to facilitate the choice of a uniform annoyance descriptor, but does not necessarily reflect the position of all members of WG2.

## 2.3. Discussion

The choice of the annoyance descriptor depends on the framework within which it is to be used. Such a framework could encompass the following three elements:

1. Elimination of unacceptable levels (black spots) by a legal limit (U) in terms of Lden, possibly linked to the type of source;
2. Preservation and extension of quiet (residential and natural) areas (white areas) by policy targets in terms of the area where Lden does not exceed a certain value (L);
3. Improvement of the acoustical quality in residential areas where L < Lden < U (grey areas) by policy targets in terms of the prevalence of annoyance.

Then relationships between Lden and annoyance are needed to estimate the prevalence of annoyance (point 3) on the basis of noise maps. With relationships for %HA, the number of highly annoyed persons can be estimated; with relationships for %A, the number annoyed persons can be estimated. Alternatively, with relationships for the average annoyance, the ‘total amount of annoyance’ (Norwegian noise annoyance index = sum of estimated annoyance scores in the population) can be assessed.

%HA has been most widely used. An important practical advantage over %A is that calculation of the number of annoyed persons using %A does require very low levels down to Lden = 37 dB(A) to be assessed, while determination of the number of highly annoyed persons using %HA does not require information on levels with Lden < 42 dB(A). An advantage of percentage measures such as %HA and %A over the average annoyance is that the corresponding prevalence measures (number of highly annoyed persons, number of annoyed persons) are more easily understood by the public than prevalence measures on the basis of the average annoyance (noise annoyance index). Finally, experience made clear that the higher sensitivity of %HA to changes in the higher range of Lden and the lower sensitivity to changes in the lower range of Lden actually may be an advantage. Substantive reduction of any prevalence measure of annoyance (based on %HA, %A, or average annoyance) requires improvements in the lower part of the range between L and U, because the largest part of the population comes in that part of the range. In order to draw sufficient attention to persons in the higher part of grey areas, exposed to levels close to a legal limit (U), it appears to be an advantage that %HA is relatively sensitive to noise reductions in that range. There is no danger of neglecting quiet areas as a consequence of using %HA as the annoyance descriptor, if there is a separate stimulating the preservation and extension of quiet areas (white areas) (point 2).

# III - RECOMMENDATIONS

The Position Paper recommends the use of the following relationships for the estimation of the noise annoyance (%A and % HA) on the basis of the noise exposure of dwellings. The exact formulas for the relationships that have been found (see Annex I) involve the formula for a normal distribution. The following polynomial approximations are easier to use and are sufficiently accurate for practical purposes:

Aircraft: $\%A = 8.588*10^{-6} (Lden-37)^3 + 1.777*10^{-2} (Lden-37)^2 + 1.221 (Lden-37)$;
Road traffic: $\%A = 1.795*10^{-4} (Lden-37)^3 + 2.110*10^{-2} (Lden-37)^2 + 0.5353 (Lden-37)$;
Railways: $\%A = 4.538*10^{-4} (Lden-37)^3 + 9.482*10^{-3} (Lden-37)^2 + 0.2129 (Lden-37)$;

Aircraft: $\%HA = -9.199*10^{-5} (Lden-42)^3 + 3.932*10^{-2} (Lden-42)^2 + 0.2939 (Lden-42)$;
Road traffic: $\%HA = 9.868*10^{-4} (Lden-42)^3 - 1.436*10^{-2} (Lden-42)^2 + 0.5118 (Lden-42)$;
Railways $\%HA = 7.239*10^{-4} (Lden-42)^3 - 7.851*10^{-3} (Lden-42)^2 + 0.1695 (Lden-42)$.

Figures 1 and 2 show that the approximations (dashed lines) are almost equal to the curves estimated on the basis of empirical data (solid lines). The figures also show the 95% confidence intervals around the curves (dotted lines).

Curves for annoyance using any cut-off (50,72, or another) can be derived on the basis of the information presented in the Annex of this Position Paper. Table 1 gives for various Lden values %A as well as %HA. The table illustrates that for one type of source there is a one-to-one correspondence between %A and %HA. Consequently, for each limit in terms of %A there is an equivalent limit in terms of %HA (i.e., a %HA that corresponds to the same Lden). Vice versa, for each limit in terms of %HA there is an equivalent limit in terms of %A.

*Table 1. % A and % HA at various noise exposure levels (Lden) for aircraft, road traffic, and rail traffic*

| Lden | Aircraft | | Road traffic | | Rail traffic | |
|---|---|---|---|---|---|---|
| | %A | %HA | %A | %HA | %A | %HA |
| 45 | 11 | 1 | 6 | 1 | 3 | 0 |
| 50 | 19 | 5 | 11 | 4 | 5 | 1 |
| 55 | 28 | 10 | 18 | 6 | 10 | 2 |
| 60 | 38 | 17 | 26 | 10 | 15 | 5 |
| 65 | 48 | 26 | 35 | 16 | 23 | 9 |
| 70 | 60 | 37 | 47 | 25 | 34 | 14 |
| 75 | 73 | 49 | 61 | 37 | 47 | 23 |

*Figure 1: The percentage annoyed persons (%A) as a function of the noise exposure of the dwelling (Lden). The solid lines are the estimated curves, and the dashed lines are the polynomial approximations. The figure also shows the 95% confidence intervals (dotted lines).*

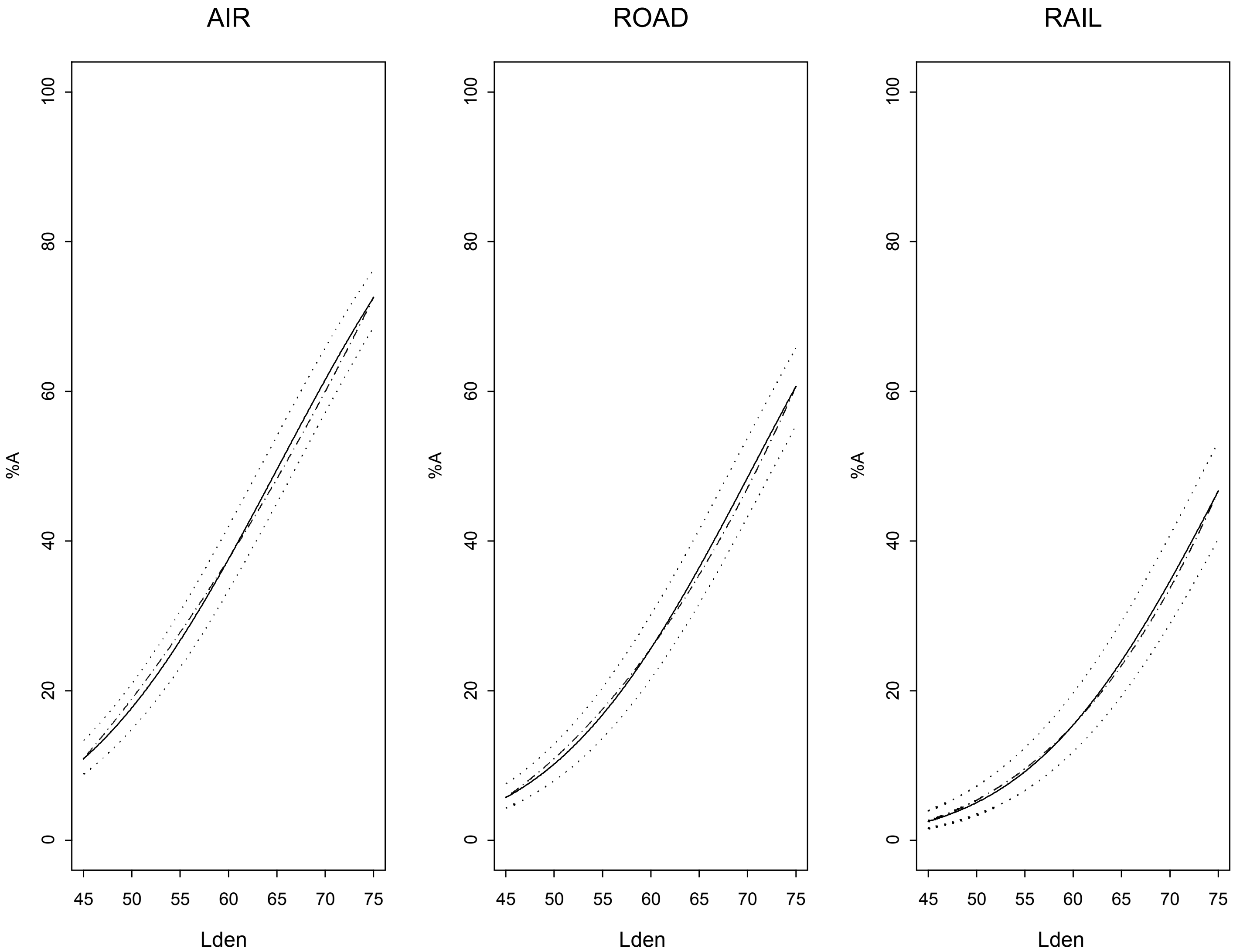
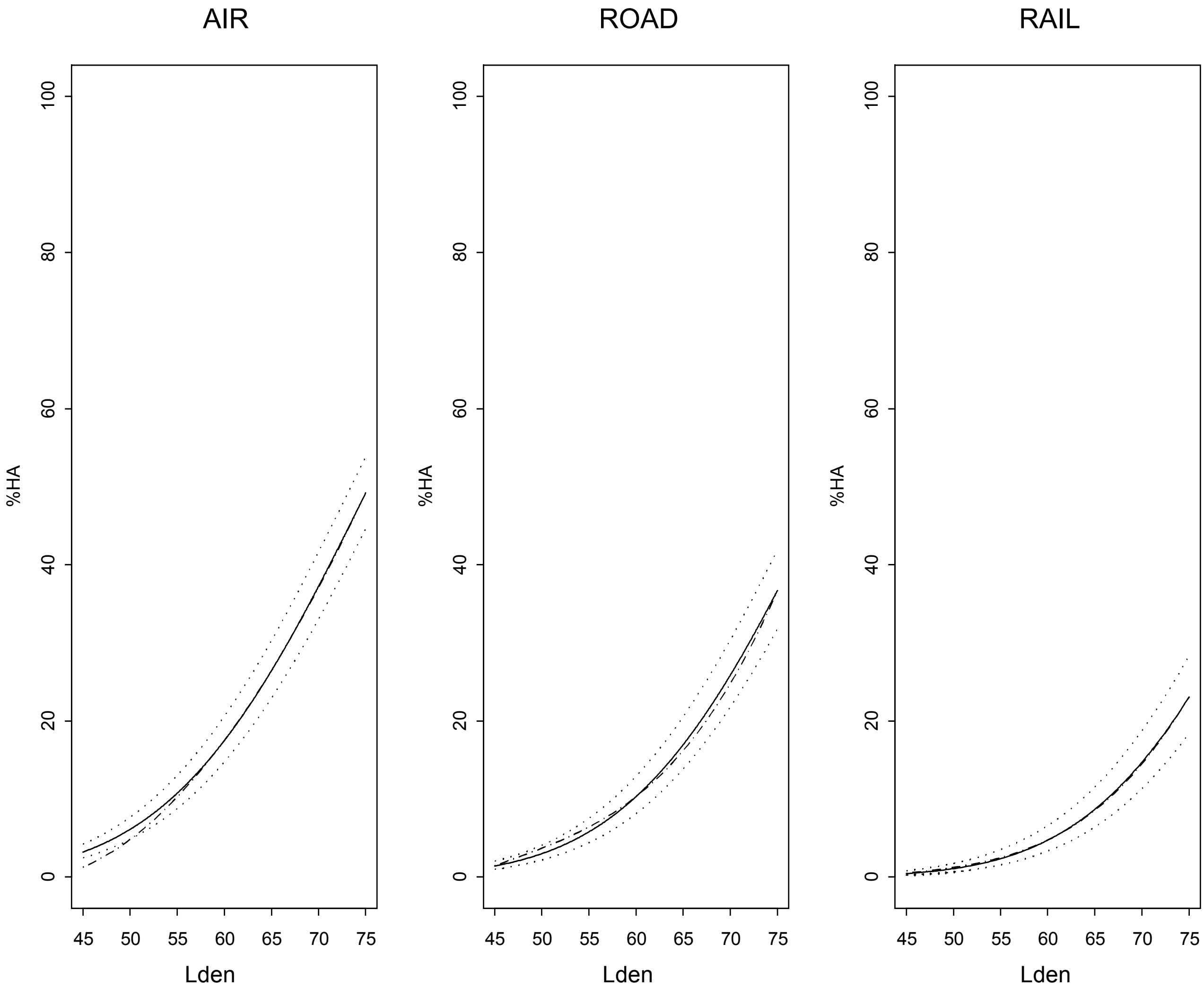


*Figure 2: The percentage highly annoyed persons (%HA) as a function of the noise exposure of the dwelling (Lden). The solid lines are the estimated curves, and the dashed lines are the polynomial approximations. The figure also shows the 95% confidence intervals (dotted lines).*



# IV - APPLICATIONS AND LIMITATIONS

The dose-response functions and their curves recommended here are only to be used for aircraft, road traffic, and railway noise and for assessment of long term stable situations. They are to be utilised for strategic assessment, in particular in the context of Annex III of the proposal for a Directive relating to the assessment and management of environmental noise, in order to assess the effects of noise on populations in terms of annoyance. They can be used in target setting, in translating noise maps into overviews of numbers of persons annoyed (or highly annoyed, etc), in cost-benefit analysis and Environmental Health Impact Assessment. When used in Environmental Health Impact Assessment, they give insight in 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.

The curves have been derived for adults. The curves are not recommended for specific sources such as helicopters, military low-flying aircraft, train shunting noise, shipping noise or aircraft noise on the ground [taxi-ing].

# V - FUTURE DEVELOPMENTS

Relationships are presented in this Position Paper for aircraft, road traffic and railways, respectively. These are the most important sources of environmental noise in Europe. However, locally, the noise situation can be dominated by other types of sources. Specifically for such situations, there is a need for procedures that can be used to estimate the annoyance caused by these other types of sources, such as industrial sources.

Also it has been acknowledged that some of the surveys included in the analyses were conducted some time ago when, for example, a different range of aircraft types were in use at certain airports. Work is in progress to add the most recent surveys to the database and also to conduct new surveys. Analyses to be published in the next year do no reveal any systematic changes of the dose-response functions over the time span (1965-1998) covered by the data sets used to establish the functions presented here.

Furthermore, there is a need for quantifying the influence on annoyance of a relatively quiet façade, special insulation, and possible differences between Northern and Southern Member States of the EU.

Working groups will pay attention to these issues in the coming years and will formulate an update of the present Position Paper if sufficient insights in these issues will be gained in that period.

**Annex I**

**TNO Report PG/VGZ/00.052**

# Elements for a position paper on relationships between transportation noise and annoyance

**July 2000**

(Results also published as: Miedema HME, Oudshoorn CGM. Annoyance from Transportation Noise: Relationships with Exposure Metrics Ldn and Lden and their Confidence Intervals. *Environmental Health Perspectives*, Vol. 109, 4, April 2001).

## Annex II: Dates and History - Members of WG 2

**WG 2 Meeting, 14 January 2000 (NPL, Teddington):** Preliminary draft of exposure response relationships for noise annoyance for the Position Paper presented by Henk Miedema. Discussion followed.

**WG2 Meeting, 12 May 2000 (Ministry of the Environment, Paris):** Henk Miedema made a presentation of a paper to be submitted to a scientific journal. This paper will be the background for the position paper. Discussion followed.

**WG2 Meeting, 31 August 2000 (Nice):** The commissioned TNO report (PG/VGZ/00.052, July 2000) prepared by Henk Miedema and Catharina Oudshoorn has already been accepted by the Commission. A draft of the WG 2 Interim position paper will be produced by Bernard Berry and Henk Miedema on the basis of this TNO report. Comments of WG members will be submitted to Jacques Lambert (no later than 22 September 2000).

**Steering Group Meeting (Brussels, 13 October 2000):** Approval of WG2 position paper on dose-effect relations on the agenda. Jacques Lambert (Chairman of WG 2) presented the position paper. Discussion followed. SG members to provide comments to Cion by 15 December 2000.

**WG2 Meeting 26 January 2001 (City of Amsterdam):** Comments of the Steering Group to the WG 2 Position paper and revision of the Position paper (Jacques Lambert and Henk Miedema). Discussion followed

**Steering Group Meeting (Brussels, 5 June 2001):** Presentation of the revised Position Paper by Jacques Lambert (Chairman WG 2). SG members to provide comments to Cion by 15 July 2001.

**Steering Group Meeting (Brussels, 7 December 2001):** In the absence of Jacques Lambert (Chairman WG 2), Martin van den Berg presented WG2's position paper on dose-effect relations for the Lden indicator. CION thanked WG2 for their work, and asked them to finalise the paper with the full group, including a recommendation to the CION to publish the paper as an input to Annex III of the Environmental Noise Directive. WG 2 members to provide final comments to J. Lambert by 31 December 2001.

**The members of WG2 are:**
Jacques Lambert (chair), INRETS, France
Birgitta Berglund (co-chair), University of Stockholm, Sweden
Bernard F. Berry, NPL/ Bel-Acoustics, UK
Ton van Breemen, City of Amsterdam, Netherlands
Andrea Franchini, Agenzia Regionale Prevenzione e Ambiente, Italy
Isabel Lopez Barrio, Instituto de Acustica, Spain
Henk M.E. Miedema, TNO, Netherlands
Jens Ortscheid, Umweltbundesamt, Germany
Jose Palma (NGO - Quercus), University of Lisboa, Portugal
Tjeert ten Wolde, EC, Belgium
Shirley J. Thompson (WHO), University of South Carolina, USA
Ian Witter (ACI Europe), BAA Heathrow, UK

*TNO report*
PG/VGZ/00.052

# Elements for a position paper on relationships between transportation noise and annoyance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**CONTENTS**

## *PREFACE*

The EU is preparing an environmental noise policy. As a part of the preparation of a directive on environmental noise, several working groups are preparing position papers. The work reported here arose from the Working Group Dose/Effects[1], which has the task to provide relationships between noise exposure and noise effects. To support this working group, EU/DG Environment requested TNO to establish exposure response relationships for noise annoyance on the basis of the large international archive of noise annoyance studies at TNO. TNO was asked to pay special attention to the methodology of establishing the relationships, and to report the results in a form that can be easily transformed into a position paper. This report presents the results in the following "Elements for a Position Paper on relationships between transportation noise and annoyance".
As much as possible, the views that have been expressed in the meetings of Working Group Dose/Effects have been taken into account by the author, who is a member of the working group. Helpful comments on a draft have been given by dr B. Berry from NPL in the United Kingdom, also a member of the working group. At this point in time, however, only the author of this report is responsible for the views presented. In its meeting scheduled at 31 August 2000 in Nice, the Working Group Dose/Effects plans to discuss its position paper on this subject matter. This report is offered as input for that discussion.

[1] The members of Working Group Dose/Effects are:
Jacques Lambert (chair), INRETS, France;
Birgitta Berglund (Co Chair), Stockholm University, Sweden;
Bernard. F. Berry, NPL, United Kingdom;
Ton van Breemen, City of Amsterdam, Netherlands;
Andrea Franchini, Agenzia Regionale Prevenzione e Ambiente, Italy;
Isabel Lopez Barrio, Instituto de Acústica, Spain;
Henk M.E. Miedema, TNO, Netherlands;
Jens Ortscheid, Umweltbundesamt, Germany;
Jose M. Palma (NGO – Quercus), Universidade de Lisboa, Portugal;
Tjeert ten Wolde, EC, Belgium;
Shirley J. Thompson (WHO), University of South Carolina, USA;
Ian Witter (ACI Europe), BAA Heathrow, UK.

## *ELEMENTS FOR A POSITION PAPER ON RELATIONSHIPS BETWEEN TRANSPORTATION NOISE AND ANNOYANCE*

### Introduction

For making policy against environmental noise, it is important to have a set of relationships that show which annoyance level is associated with a given noise exposure level. Many studies have been conducted to establish such relationships. This Position Paper recommends synthesis curves for aircraft, road traffic and railway noise that are based on studies conducted in Europe, North America and Australia. They are presented together with their confidence intervals. These relationships can be used to estimate the number of annoyed persons, given the noise exposure of their dwellings. The full technical development of these relationships is described in a Technical Annex to this Position Paper.

### State of the art

Synthesis curves based on an extensive set of data have been presented for aircraft, road traffic, and railway noise recently[2]. These curves were based on all studies examined earlier[3] for which LDN and percentage highly annoyed persons (%HA) meeting certain minimal requirements could be derived, augmented with a number of additional studies. Consequently, the recent synthesis was more comprehensive than the previous ones. Moreover, the kind of errors and inaccuracies found[4] in the previous syntheses were avoided.

In the technical annex the same data are analyzed, but the model of the relationship between exposure and annoyance is more sophisticated and better suited for the data. Usage of the more appropriate model gives the relationships and their confidence intervals a firmer base. The Technical Annex does not only present relationships with DNL as the descriptor of the noise and %HA as the descriptor of the noise annoyance. Among others, it also presents relationships with LDEN as the descriptor of the noise and the percentage annoyed persons (%A) as the descriptor of the noise annoyance. Relationships between LDEN and %A are of special importance, because LDEN has been selected as the metric for the European Union, and this Position Paper recommends %A as the descriptor of annoyance.

### Noise metric

LDEN is defined in terms of the "average" levels during daytime, evening, and night-time, and applies a 5 dB penalty to noise in the evening and a 10 dB penalty to noise in the night. The definition is as follows:

$$LDEN \quad = \quad 10 \lg [(12/24).10^{LD/10} + (4/24).10^{(LE+5)/10} + (8/24).10^{(LN+10)/10}]$$

Here LD, LE, and LN are the A-weighted long term $L_{Aeq}$ as defined in ISO 1996-2 (1987) for the day (7-19h), evening (19-23h), and night (23-7h) determined over the year at the most exposed facade. LDEN has been put forward as one of the two main noise metrics in a proposal for a Directive for the Assessment and Management of Environmental Noise[5].

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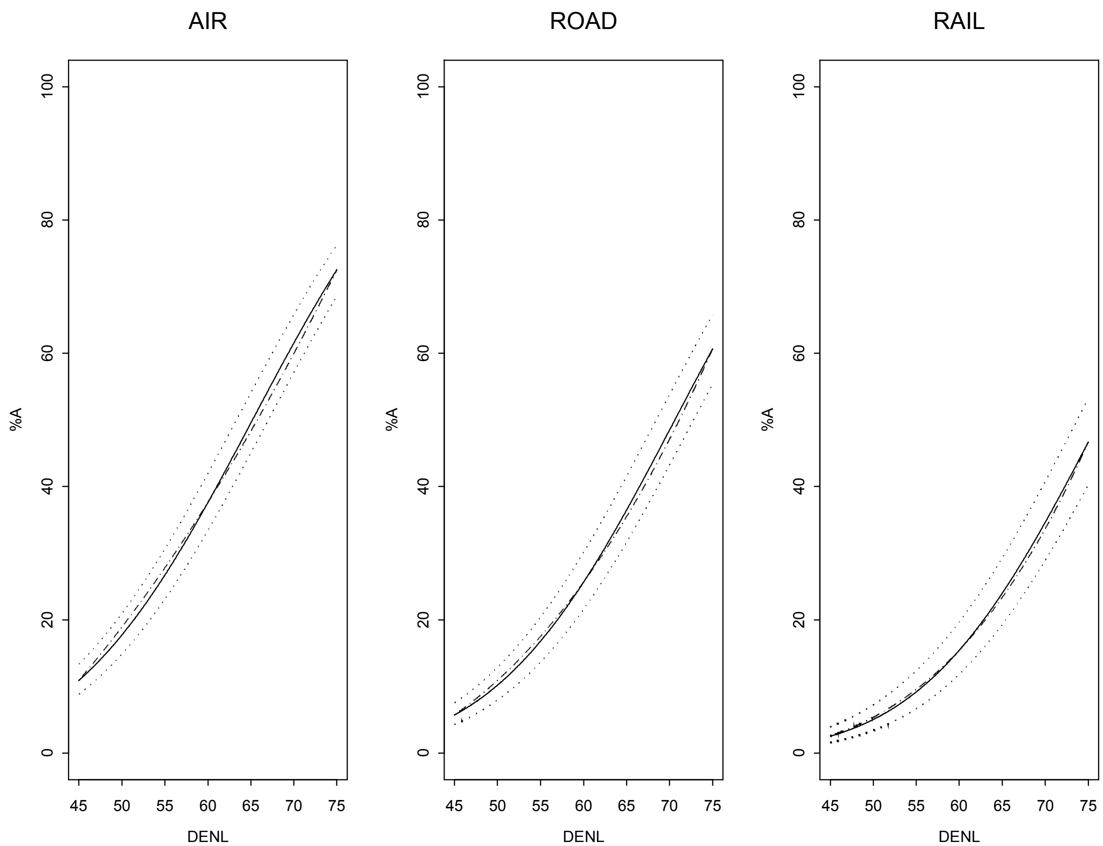
[2] Miedema M.E. and H.Vos (1998). Exposure-response relationships for transportation noise. J. Acoust. Soc. Am. **104** (6).

[3] Schultz T.H.J. (1978). Synthesis of soical surveys on noise annoyance. J. Acoust. Soc. Am. **64** 377-405. Fidell,S, Barber D.S., and Schultz Th. J. (1991). Updating a dosage effect relationship for the prevalence of annoyance due to general transportation noise. J. Acoust. Soc. Am. **89** 221-233.

[4] Fields J.M. (1994). A review of an updated synthesis of noise/annoyance relationships. NASA Report 19450. Georgia Institute of Technology. Atlanta, GA.

[5] EU/DG Environment (2000). Proposal for a European Parliament and Council Directive on the approximation of the laws of the Member States relating to the Assessment and Reduction of Environmental Noise, EU/DG Environment, Brussel, DG ENV Working Draft. Also see: Working Group on Noise Indicators (1999). Position Paper on EU noise indicators. Commission of the European Communities

*Figure 1: The percentage annoyed persons (%A) as a function of the noise exposure of the dwelling (LDEN). The solid lines are the estimated curves, and the dashed lines are the polynomial approximations. The figure also shows the 95% confidence intervals (dotted lines).*




**Annoyance measure**

Annoyance questions in different studies do not use the same number of response categories. Some questions have only three response categories while others use as many as eleven categories. In order to obtain comparable annoyance measures for different studies, all sets of response categories can be 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 distribution of the annoyance scores on the scale from 0 to 100 at a given noise exposure level can be summarized in various ways. Often a cutoff point is chosen and the percentage of responses exceeding the cutoff is reported. If the cutoff is 72 on a scale from 0 to 100, then the result is called the percentage 'highly annoyed' (%HA), and if the cut-off is 50 then the result is called the percentage 'annoyed'. The %HA has often been used as the descriptor of the noise annoyance. Here, however, it is not adopted, because is does not sufficiently reflect the changes in annoyance that occur at lower noise exposure levels. These are mainly changes in annoyance levels below 72 on a scale from 0 to 100, to which %HA is insensitive. This Position Paper recommends %A as the descriptor of noise annoyance.

**Relationships between LDEN and %A**

The Position Paper recommends the use of the following relationships for the estimation of the noise annoyance on the basis of the noise exposure of dwellings. The exact formulas for the relationships that have been found (see Technical Annex) involve the formula for a normal distribution. The following polynomial approximations are easier to use and are sufficiently accurate for all practical purposes:

Aircraft: $\%A = 1.343*10^{-6} (LDEN-37)^3 + 1.904*10^{-2} (LDEN-37)^2 + 1.175 (LDEN-37)$;
Road traffic: $\%A = 1.927*10^{-4} (LDEN-37)^3 + 2.560*10^{-2} (LDEN-37)^2 + 0.3490 (LDEN-37)$;
Rail traffic: $\%A = 5.124*10^{-4} (LDEN-37)^3 + 8.271*10^{-3} (LDEN-37)^2 + 0.1625 (LDEN-37)$.

Figure 1 shows that the approximations (dashed lines) are almost equal to the estimated curves (solid lines). The figure also shows the 95% confidence intervals around the curves dothed lines.

**Validity and accuracy of the relationships**
The quality of the presented curves can be judged relative to the quality of curves and thresholds that are being used for evaluating other environmental pollutants. Based on the following observations, the validity of the presented noise annoyance curves is considered to be relatively very high.
The validity of curves and thresholds depends to a large extent on the validity of the data on which they are based. The recommended relationships between noise exposure and annoyance are based on the data from a large set of field studies in which data on noise exposure and noise annoyance were collected. For most effects of other environmental pollutants, there are only limited or no data from epidemiological studies with subjects exposed in their living environment to levels in the relevant range. Often only data from animal studies are available, which must be extrapolated to effects in 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 and effects of long-term low exposures. Sometimes human data concerning high exposures at work or after accidents are available, for which only the latter type of extrapolation is needed. The derivation of the relationships between noise exposure and annoyance did not involve the types of assumptions mentioned, because noise annoyance has been studied extensively directly with humans in the relevant exposure situations. It is safe to state that 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.
Validity of relationships means that there is no systematic error in their estimation. Another point of concern is uncertainty due to random errors. The uncertainty regarding the exact location of curves caused by random errors can be described by confidence intervals. The noise annoyance curves have rather narrow confidence intervals. This means that the location of these curves in the entire population is known rather accurately.

**Application**
Substantial deviations from the predicted percentage annoyed persons must be expected for limited groups at individual sites 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, 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 particularities of the persons and their actual circumstances. For similar reasons, a 'norm' curve also can be used to estimate the number of annoyed persons in the vicinity of an airport, road, or railway when different scenarios concerning, e.g., extension of these activities or emission reductions 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 to be an advantage 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 use of 'norm curves' or 'norm thresholds', which are valid

for the entire population (or a particular sensitive subgroup), is common practice when exposures to other environmental pollutants, such as air pollutants or radiation, are evaluated. There they are used for the evaluation of an individual situation, irrespective of the population in that situation. It is recommended to take the same approach in the case of environmental noise and use the same curve irrespective of the population in the situation evaluated.

**Future improvements**

Relationships are presented in this Position Paper for aircraft, road traffic and railways, respectively. These are the most important sources of environmental noise in Europe. However, locally the noise situation can be dominated by other types of sources. Specifically for such situations, there is a need for procedures that can be used to estimate the annoyance caused by these other types of sources, such as industrial sources.

An important elaboration of the relationships presented for aircraft, road traffic and railways would be the inclusion of more (exposure) variables as predictors of annoyance, in addition to LDEN (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 the 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 LDEN, the sound insulation of the dwelling, and the level at the most quiet side of the dwelling.

Another important improvement of our knowledge in the long-term would be a model of noise-induced effects that describes how effects such as speech disturbance and sleep disturbance affect noise annoyance, and that also describes the relation between noise annoyance and somatic stress reactions.

A model that includes more predictors and specifies the interrelations between different effects would extend our knowledge of the statistical relationship between noise exposure and annoyance with insight into the mechanisms that cause this association.

# *TECHNICAL ANNEX*

## Annoyance from transportation noise: relationships with exposure metrics *DNL* and *DENL*, and their confidence intervals

### 1. Introduction

For making policy against environmental noise, it is important to have a set of relationships that show which annoyance level is associated with a given noise exposure level. Many studies have been conducted to establish such relationships. However, doubt regarding the predictability of noise annoyance impedes the acceptance of exposure response relationships that have been proposed.
One cause of this doubt is that the studies conducted 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 (Schultz, 1978; Fidell et al, 1991; Miedema and Vos, 1998) 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 satisfying 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 large uncertainty. This uncertainty can be described by the *prediction interval* for individuals or groups, respectively, 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 not the uncertainty with respect to the prediction of an individual or group reaction is important, but 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 subtle. This paper presents a type of exposure response curve that has been established earlier, and, in addition, curves with other descriptors of the exposure and other descriptors of the annoyance, together with the confidence intervals of these curves.

Miedema and Vos (1998) presented synthesis curves for aircraft, road traffic, and railway noise. These curves were based on all studies examined by Schultz (1978) and Fidell, Barber, and Schultz (1991) for which *DNL* and percentage highly annoyed persons (*%HA*) meeting certain minimal requirements could be derived, augmented with a number of additional studies. Consequently, that synthesis was more comprehensive than the previous ones. Moreover, the kind of errors and inaccuracies Fields (1991) found in the previous syntheses were avoided. Miedema and Vos (1998) made an attempt to find the 95% confidence intervals around the exposure response curves, taking into account the variation between individuals and studies.

Here the method they used to establish the confidence intervals is improved upon substantially. The same data are analyzed, but the model of the relationship between exposure and annoyance is more sophisticated and better suited for the data. Usage of the more appropriate model gives the relationships and their confidence intervals a firmer basis. The resulting relationships and their 95% confidence intervals turn out to not differ much from the ones published previously. The confidence intervals indicate that, even though there is considerable variation between individuals and between studies, the uncertainty regarding the location of the 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 on the basis of the results presented in this paper. In addition to the relationships between *DNL* and annoyance, relationships that use another noise metric (*DENL*) are presented. *DENL* has been proposed as the noise exposure metric for the European Union (EU/DG Environment, 2000). Relationships using descriptors other than *DNL* and *%HA* and based on a large dataset, have not been published earlier.

## 2. Noise metrics and annoyance measures

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

$$DNL \quad = \quad 10 \lg [(15/24).10^{LD/10} + (9/24).10^{(LN+10)/10}]$$

Here *LD* and *LN* are the $L_{Aeq}$ as defined in ISO 1996-2 (1987) for the day (7-22h) and the night (22-7h), respectively.
A noise metric related to *DNL* is the day-evening-night level, *DENL*. It is defined in terms of the "average" levels during daytime, evening, and night-time, and applies a 5 dB penalty to noise in the evening and a 10 dB penalty to noise in the night. The definition is as follows:

$$DENL \quad = \quad 10 \lg [(12/24).10^{LD/10} + (4/24).10^{(LE+5)/10} + (8/24).10^{(LN+10)/10}]$$

Here *LD*, *LE*, and *LN* are the A-weighted long term $L_{Aeq}$ as defined in ISO 1996-2 (1987) for the day (7-19h), evening (19-23h), and night (23-7h) determined over the year at the most exposed facade. *DENL* has been proposed as the new uniform noise metric for the European Union (EU/DG Environment, 2000).
The use of *DNL* or *DENL* is supported by a recent publication from Miedema et al (2000), who investigated which noise metrics best predict annoyance from aircraft noise. They concluded that the outcome of their analyses of available datasets supports the use of metrics based on $L_{Aeq}$*'s* and the application of a 10 dB penalty to nighttime noise. The available data was not a suitable basis for a conclusion regarding a penalty for noise in the evening.

Annoyance questions in different studies do not use the same number of response categories. Some questions have only three response categories while others use as many as eleven categories. In order to obtain comparable annoyance measures for different studies, 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. Then the general rule that gives the position of a category boundary on a scale from 0 to

100 is: $score_{boundary\ i} = 100i/m$ (see 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 from 0 to 100 and the percentage of the responses exceeding the cutoff is reported. If the cut-off is 72 on a scale from 0 to 100, then the result is called the percentage 'highly annoyed' persons (*%HA*), with a cutoff at 50 it has been called the percentage 'annoyed' (*%A*), and with a cutoff at 28 the percentage '(at least) a little annoyed' (*%LA*). An alternative to these types of measures is the average annoyance score.

## 3. Data

In the last seven years TNO in Leiden has compiled an archive of original datasets 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 criteria presented in Miedema and Vos (1998). Extreme exposure levels (*DNL* < 45 or > 75 dB) were excluded from the analyses. The derivation of *DNL* and *%HA* has been discussed in that publication. Here that discussion is supplemented with a discussion of the derivation of the additional measures that are used in this paper.

Here *DENL* is also used as a descriptor of the noise exposure, as a possible alternative for *DNL*. For most studies in table 2 the $L_{Aeq}$'s (for the periods 7-19h, 19-23, and 23-7h) that are needed for calculating *DENL* (see section 2) could be derived in the same way as the $L_{Aeq}$'s (for the periods 7-22 and 22-7h) that are needed for calculating *DNL*. This derivation has been described in Miedema and Vos (1998). However, *DNL* was given or estimated directly for various studies, indicated in table 2, and no information regarding the time pattern of the $L_{Aeq}$'s 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 night-time curfew. For Sydney and Adelaide such a curfew existed so that 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. Therefore a better rule in this case was: *DENL* = *DNL* + 0.3.

Here the distribution of annoyance responses is modelled as a function of the noise exposure (see section 4). 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. For most studies in table 2 this information was available (see Miedema and Vos, 1998). For some studies, not the distribution of the response over the original annoyance categories was known, but only the percentage 'highly annoyed' (and the percentage not 'highly annoyed'). Since 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.
A specific procedure was applied 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 e.g. the procedure in Miedema and Vos (1998) where only the relationship of *%HA* with the noise exposure was modelled. 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 joint if a filter has been used, and the respondents who skipped the annoyance question were assigned to this joint category.

## 4. Exposure response model

### 4.1 Basic model

The noise annoyance of an individual on a scale from 0 to 100 is denoted by $A^*$. Instead of observing the noise annoyance $A^*$ precisely, it is only known for an individual in which interval on the scale from 0 to 100 $A^*$ comes. The locations of the boundaries of the intervals depend on the set of annoyance response categories used in a study (see section 2).

$A^*$ 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:

$$A^* = \beta_0 + \beta_1\, DNL + \varepsilon^* \qquad (4.1^*)$$

Here $\beta_0$ is the intercept, $\beta_1$ is the slope coefficient of *DNL,* and $\varepsilon^*$ is the random component. The random component, $\varepsilon^*$, and hence $A^*$ is assumed to have a censored normal distribution[6]. 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 follows.
$A^*$ 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 $\varepsilon^*$ and hence $A^*$ is assumed to be censored normal. Instead of considering the annoyance variable $A^*$, it is more convenient to model the corresponding, normally distributed variable $A$. Then the model is:

$$A = \beta_0 + \beta_1\, DNL + \varepsilon, \qquad (4.1)$$

where $\varepsilon$ is normally distributed with zero mean and constant variance $\sigma^2$, i.e. $\varepsilon \sim N(0, \sigma^2)$. The parameters of model (4.1) can be estimated with so-called grouped regression analysis (see Long, 1997) if not $A$ but only the interval in which $A$ comes is observed, as is the case.

A common type of measure of annoyance is the percentage of people whose annoyance exceeds a certain annoyance level $C$. In the sequel this will be the main descriptor of the annoyance

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[6] A random variable $X$ with bounded support $[\tau_L, \tau_R]$ has a censored normal distribution with parameters $\mu$, $\sigma$, $\tau_L$ and $\tau_R$ (the left and right censoring points) if its density equals $\phi((x - \mu)/\sigma)$ for $x \in ]\tau_L\ \ \tau_U[$ 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.

distribution of interest. The probability $p_C(DNL)$ that someone with exposure $DNL$ has an annoyance level that exceeds $C$ is:

$$
\begin{aligned}
p_C(DNL) &= Prob(\ A \geq C\ ) \\
&= Prob(\beta_0 + \beta_1\ DNL + \varepsilon \geq C) \\
&= Prob(\varepsilon \geq C - \beta_0 - \beta_1\ DNL\ ) \\
&= 1 - \Phi((C - \beta_0 - \beta_1\ DNL)/\sigma), \qquad (4.2)
\end{aligned}
$$

where $\Phi$ represents the cumulative standard normal distribution[7].
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 $\beta_0$ and the slope $\beta_1$, and estimate $s$ of the standard error $\sigma$, respectively, then $\hat{p}_C(DNL) = 1 - \Phi((C - b_0 - b_1\ DNL)/s)$ 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 sequel 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.

## 4.2 Extended model

In standard regression models it is assumed that individuals have been drawn at random from a population and that the random components $\varepsilon$ for the individuals are independent. However, the individuals in the present multi-study dataset 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 it is well-known that in noise annoyance investigations there is a large study effect, it is important to take this aspect of the dataset into account. An accepted method of incorporating study effects is formulating a multilevel model (see e.g. Goldstein, 1995). A multilevel version of models such as (4.1), of which the parameters can be estimated by grouped regression, has been studied by Keen and Engel (1997).

Including a study effect on the intercept of the relationship specified in model (4.1) gives (using individual index $i$ and study index $j$):

$$A_{ij} = \beta_0 + \beta_1 DNL_{ij} + u_{0j} + \varepsilon_{ij}, \qquad (4.3)$$

where $u_{0j}$ is a random study factor, normally distributed with zero mean and variance $\sigma_0^2$. According to this model the relation between $DNL$ and annoyance can have a different intercept in each study. The average intercept is equal to $\beta_0$. The total random component in model (4.3) is equal to $u_{0j} + \varepsilon_{ij}$. This means that the observations within one study are not independent.

Using model (4.3), 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.

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

The probability conditional on the random study factor $u_0$ is:

$$p_C(DNL \mid u_0) = Prob(A \geq C \mid u_0)$$

$$= Prob(\varepsilon \geq C - \beta_0 - \beta_1\, DNL - u_0 \mid u_0).$$

Using this and the assumption that $u_0$ is normally distributed with mean zero and variance $\sigma_0^2$, the following result can be obtained:

$$p_C(DNL) = Prob(\beta_0 + \beta_1\, DNL + u_{0j} + \varepsilon \geq C)$$

$$= 1 - \Phi((C - \beta_0 - \beta_1\, DNL)/\sqrt{(\sigma^2 + \sigma_0^2)}). \quad (4.4)$$

The term $\sigma^2 + \sigma_0^2$ in equation (4.4) has the same role as $\sigma^2$ in equation (4.2).
To estimate the probability that the annoyance level of a randomly selected person from a randomly selected study exceeds $C$, the four parameters $\beta_0$, $\beta_1$, $\sigma_0^2$, and $\sigma^2$ 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) to obtain the estimates, because with this procedure the study effect could be properly taken into account (see SAS/STAT Online User's Guide V8, the NLMIXED Procedure, Example 46.3: Probit-Normal Model with ordinal data).
Given the estimates $b_0$, $b_1$, $s_0^2$ and $s^2$ of $\beta_0$, $\beta_1$, $\sigma_0^2$ and $\sigma^2$, respectively, the expected percentage of persons with noise exposure *DNL* whose annoyance exceeds C, can be estimated as follows:

$$100 \,.\, \hat{p}_C(DNL) = 100.\,(1 - \Phi((C - b_0 - b_1\, DNL)/\sqrt{(s^2 + s_0^2)})). \quad (4.5)$$

### 4.3 Confidence intervals

Confidence intervals are calculated as follows. Let $\boldsymbol{x}$ be the vector $(1, DNL)^t$, with *DNL* a certain noise level. Let $\boldsymbol{\Sigma_\beta}$ denote the covariance matrix of the coefficients $\beta_0$ and $\beta_1$. Furthermore, $\boldsymbol{b}$ 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

$$C_{LU} = \boldsymbol{x}^t \boldsymbol{b} \pm 1.96 \sqrt{(\boldsymbol{x}^t \boldsymbol{\Sigma_\beta} \boldsymbol{x})} \quad (4.6)$$

The confidence limits for $p_C(DNL)$ are:

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

where $s$ is an estimate of $\sigma$, $s_0$ is an estimate of $\sigma_0$ and $C_{L,U}$ is given by (4.6).

## 5. Results

Model (4.3) was fitted separately for aircraft, road traffic, and railways. 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 in figures 1 and 2 (dotted lines). The estimates of the coefficients $\beta_0$, $\beta_1$, $\sigma_0^2$, and $\sigma^2$ 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 $\sigma_0^2$ and $\sigma^2$, shows that there is for aircraft and roadtraffic a significant between study variation, 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. Approximations for *DNL* are (*%LA* is the percentage 'little annoyed'; *%A* is the percentage 'annoyed', and *%HA* is the percentage 'highly annoyed'):

Aircraft: $\%LA = -5.741*10^{-4}\,(DNL\text{-}32)^3 + 2.863*10^{-2}\,(DNL\text{-}32)^2 + 1.912\,(DNL\text{-}32)$;
Road traffic: $\%LA = -6.188*10^{-4}\,(DNL\text{-}32)^3 + 5.379*10^{-2}\,(DNL\text{-}32)^2 + 0.723\,(DNL\text{-}32)$;
Railways: $\%LA = -3.343*10^{-4}\,(DNL\text{-}32)^3 + 4.918*10^{-2}\,(DNL\text{-}32)^2 + 0.175\,(DNL\text{-}32)$;

Aircraft: $\%A = 1.460*10^{-5}\,(DNL\text{-}37)^3 + 1.511*10^{-2}\,(DNL\text{-}37)^2 + 1.346\,(DNL\text{-}37)$;
Road traffic: $\%A = 1.732*10^{-4}\,(DNL\text{-}37)^3 + 2.079*10^{-2}\,(DNL\text{-}37)^2 + 0.566\,(DNL\text{-}37)$;
Railways: $\%A = 4.552*10^{-4}\,(DNL\text{-}37)^3 + 9.400*10^{-3}\,(DNL\text{-}37)^2 + 0.212\,(DNL\text{-}37)$;

Aircraft: $\%HA = -1.395*10^{-4}\,(DNL\text{-}42)^3 + 4.081*10^{-2}\,(DNL\text{-}42)^2 + 0.342\,(DNL\text{-}42)$;
Road traffic: $\%HA = 9.994*10^{-4}\,(DNL\text{-}42)^3 - 1.523*10^{-2}\,(DNL\text{-}42)^2 + 0.538\,(DNL\text{-}42)$;
Railways: $\%HA = 7.158*10^{-4}\,(DNL\text{-}42)^3 - 7.774*10^{-3}\,(DNL\text{-}42)^2 + 0.163\,(DNL\text{-}42)$;

and for *DENL*:

Aircraft: $\%LA = -6.158*10^{-4}\,(DENL\text{-}32)^3 + 3.410*10^{-2}\,(DENL\text{-}32)^2 + 1.738\,(DENL\text{-}32)$;
Road traffic: $\%LA = -6.235*10^{-4}\,(DENL\text{-}32)^3 + 5.509*10^{-2}\,(DENL\text{-}32)^2 + 0.6693\,(DENL\text{-}32)$;
Railways: $\%LA = -3.229*10^{-4}\,(DENL\text{-}32)^3 + 4.871*10^{-2}(DENL\text{-}32)^2 + 0.1673\,(DENL\text{-}32)$;

Aircraft: $\%A = 8.588*10^{-6}\,(DENL\text{-}37)^3 + 1.777*10^{-2}\,(DENL\text{-}37)^2 + 1.221\,(DENL\text{-}37)$;
Road traffic: $\%A = 1.795*10^{-4}\,(DENL\text{-}37)^3 + 2.110*10^{-2}\,(DENL\text{-}37)^2 + 0.5353\,(DENL\text{-}37)$;
Railways: $\%A = 4.538*10^{-4}\,(DENL\text{-}37)^3 + 9.482*10^{-3}\,(DENL\text{-}37)^2 + 0.2129\,(DENL\text{-}37)$;

Aircraft: $\%HA = -9.199*10^{-5}\,(DENL\text{-}42)^3 + 3.932*10^{-2}\,(DENL\text{-}42)^2 + 0.2939\,(DENL\text{-}42)$;
Road traffic: $\%HA = 9.868*10^{-4}\,(DENL\text{-}42)^3 - 1.436*10^{-2}\,(DENL\text{-}42)^2 + 0.5118\,(DENL\text{-}42)$;
Railways $\%HA = 7.239*10^{-4}\,(DENL\text{-}42)^3 - 7.851*10^{-3}\,(DENL\text{-}42)^2 + 0.1695\,(DENL\text{-}42)$.

Figures 3 (*DNL*) and 4 (*DENL*) show that the approximations (dashed lines) are almost equal to the estimated curves (solid lines). 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 formula (4.5).

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], while the actual annoyance scores are restricted to that interval (see section 4.1). Consequently, not the mean of the estimated normal annoyance distribution, but the mean of the corresponding censored normal distribution is an estimate of the mean annoyance observed with a scale from 0 to 100.

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**APPENDIX: RELATION BETWEEN *DENL* AND *DNL***

## Expectations regarding DNL – DENL on the basis of time patterns

*DNL* has been used as the noise metric by Miedema and Vos (1998). 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 determind on the basis of (estimates of) the $L_{Aeq}$*'s* in term 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 $L_{Aeq}$(7-19h) ≥ $L_{Aeq}$(19-22h) ≥ $L_{Aeq}$(22-23h) ≥ $L_{Aeq}$(23-7h). This assumption will hold for the vast majority of situations in practice.
Assuming a decreasing pattern of $L_{Aeq}$*'s* as described above, the lowest value of *DENL – DNL* is equal to –0.06dB. This means that it can be stated without significant error that *DENL – DNL* is zero or larger. The highest value of *DENL – DNL* occurs if the (hourly) $L_{Aeq}$ remains constant until 22h and drops sharply in the hour 22-23h (and thereafter). Assuming the above described decreasing pattern of $L_{Aeq}$*'s,* the maximum value *DENL – DNL* is equal to 1.56dB. On the basis of these findings it can be roughly stated that the range of the difference *DENL – DNL* is 0 – 1.5dB.
To get a more detailed insight, the difference *DENL – DNL* has been calculated for various combinations of positive differences between the $L_{Aeq}$*'s* for the successive time intervals, namely $L_{Aeq}$(7-19h) - $L_{Aeq}$(19-22h), $L_{Aeq}$(19-22h) - $L_{Aeq}$(22-23h), and $L_{Aeq}$(22-23h) - $L_{Aeq}$(23-7h).The calculations indicated that both a constant (hourly) $L_{Aeq}$ until 22h and a sharp decrease in the hour 22-23h 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 0-1.5dB 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 23h. For trams there may be a decrease in the evening, but in general there is no sharp decrease between 22 – 23h. 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 22h and a sharp decrease in the hour 22-23h). Therefore, this difference will be close to 0 for railway noise.
In general, the road traffic noise level gradually decreases during the evening, and this decrease often is accelerated in the period 21-24h. The decrease in the noise level in the hour 22-23h will in general be smaller than 3 dB. The larger this decrease in the hour 22-23h, 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 smaller than 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 in the hour 22-23h, 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 $L_{Aeq}$'s 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 the small deviations from that line are not level dependent. Therefore, the relation between *DENL* and *DNL* is summarised in the table by the average value per dataset for the difference *DENL – DNL*. The values for the average in the table 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.

| **Aircraft** | *DENL-DNL* | N |
|---|---|---|
| FRA-239 | 1.5 | 565 |
| NET-240 | 0.6 | 573 |
| NET-371 | 0.6 | 11211 |
| 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 | 1371 |
| TRK-367 | 0.2 | 154 |
| UKD-238 | 0.3 | 536 |
| **Railway** | | |
| GER-192 | -0.1 | 966 |

**Conclusion**

On the basis of the expectations derived from the time patterns of the noise level, and the available relevant empirical evidence, it is concluded 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*.

It must be kept in mind that 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 1 Boundary quantifications for different annoyance scales.*

| number 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 |

*Tabel 2 Datasets used to establish the relationships between noise exposure and annoyance (the same as in Miedema en Vos, 1998, except for NET-361 which was not used here because the number of cases is too small for the analyses in this paper; see for some minor correction that have been applied Miedema and Vos, 1999). Per dataset it is indicated how DENL is established. If this is done directly from the basic Laeq data, then there is a blank in the column concerned. The asterix * indicates that the rules from the Appendix have been used. For three airports in AUL-210 the specific rules used are given (see text).*

| **Aircraft** | | |
|---|---|---|
| Fields' code | Name of study | determination *DENL* |
| AUL-210 | Australian Five Airport Survey (1980) | |
| | Richmond & Perth | * |
| | Sydney & Adelaide | $DENL = DNL + 1.2$ |
| | Melbourne | $DENL = DNL + 0.3$ |
| 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, 71,72, 74,76) | * |
| 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.A. Four-Airport Survey (phase I of Tracor Survey) (1967) | |
| USA-032 | U.S.A. Three-Airport Survey (phase II of Tracor Survey) (1969) | |
| USA-044 | U.S.A. 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) | * |

*Tabel 2 (continued)*

| **Road Traffic** | | |
|---|---|---|
| Fields= code | Name of the survey | determination *DENL* |
| 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 Noise Survey (1973/1975) | |
| FRA-239 | French Combined Aircraft/Road Traffic Survey (1984) | |
| FRA-364 | French 18-site Time of Day Study (1993/1994) | |
| GER-192 | German Road/Railway Noise Comparison Study (1978/1981) | |
| GER-372 | Ratingen-Dusseldorf Road Traffic/Aircraft Survey (1985/1986) | |
| GER-373 | Ratingen Road Traffic/Aircraft Study (1987) | |
| NET-106 | Dordrecht Home Sound Insulation Study (1974) | |
| NET-240 | Schiphol Combined Aircraft/Road Traffic Survey (1984) | |
| NET-258 | Amsterdam Home Sound Insulation Study (1975) | |
| 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) | |

*Table 2 (continued)*

| **Railway** | | |
|---|---|---|
| Fields= code | Name of the survey | determination *DENL* |
| 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*) | n.a. |
| 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) | |

*Table 3: The estimated coefficients of model* (4.3) *using DNL as noise exposure metric for aircraft, road traffic and railways separately, with standard errors and p-values.*

Aircraft (total number of observations = 27081, number of studies = 19)

| Parameter | Estimate | Standard Error | p-value |
|---|---|---|---|
| $\beta_0$ | -89.67 | 3.30 | <.0001 |
| $\beta_1$ | 2.16 | 0.0406 | < .0001 |
| $\sigma_0^2$ | 81.05 | 26.93 | 0.0075 |
| $\sigma^2$ | 1185.90 | 20.11 | < .0001 |

Road traffic (total number of observations = 19172, number of studies = 26)

| Parameter | Estimate | Standard Error | p-value |
|---|---|---|---|
| $\beta_0$ | -105.72 | 3.89 | < .0001 |
| $\beta_1$ | 2.21 | 0.0473 | < .0001 |
| $\sigma_0^2$ | 150.32 | 42.93 | 0.0018 |
| $\sigma^2$ | 1150.08 | 18.65 | < .0001 |

Railways (total number of observations = 7632, number of studies = 8)

| Parameter | Estimate | Standard Error | p-value |
|---|---|---|---|
| $\beta_0$ | -107.45 | 6.16 | < .0001 |
| $\beta_1$ | 2.06 | 0.0819 | < .0001 |
| $\sigma_0^2$ | 51.01 | 26.90 | 0.0998 |
| $\sigma^2$ | 1043.43 | 44.32 | < .0001 |

*Table 4: The estimated coefficients of model* (4.3) *using DENL as noise exposure metric, separately for aircraft, roadtraffic and railways with standard errors and p-values.*

Aircraft (total number of observations = 27081, number of studies = 19)

| Parameter | Estimate | Standard Error | p-value |
|---|---|---|---|
| $\beta_0$ | -91.42 | 3.30 | <.0001 |
| $\beta_1$ | 2.17 | 0.0407 | <.0001 |
| $\sigma_0^2$ | 77.64 | 25.83 | 0.0076 |
| $\sigma^2$ | 1187.11 | 20.13 | <.0001 |

Road traffic (total number of observations = 19 172, number of studies = 26)

| Parameter | Estimate | Standard Error | p-value |
|---|---|---|---|
| $\beta_0$ | -106.97 | 3.91 | <.0001 |
| $\beta_1$ | 2.22 | 0.0476 | <.0001 |
| $\sigma_0^2$ | 150.54 | 42.99 | 0.0018 |
| $\sigma^2$ | 1150.71 | 18.66 | <.0001 |

Railways (total number of observations = 7 632, number of studies = 8)

| Parameter | Estimate | Standard Error | p-value |
|---|---|---|---|
| $\beta_0$ | -110.09 | 6.33 | <.0001 |
| $\beta_1$ | 2.10 | 0.0840 | <.0001 |
| $\sigma_0^2$ | 53.86 | 28.55 | 0.1013 |
| $\sigma^2$ | 1078.73 | 47.21 | <.0001 |

Figure 1: For aircraft, road traffic and railways *%LA* (upper row), *%A* (middle row) and *%HA* (lower row) as a function of *DNL*, together with the 95% confidence intervals. The curves were found by fitting model (4.3) to the data from field surveys (see table 2). The estimates of the parameters are given in table 3.

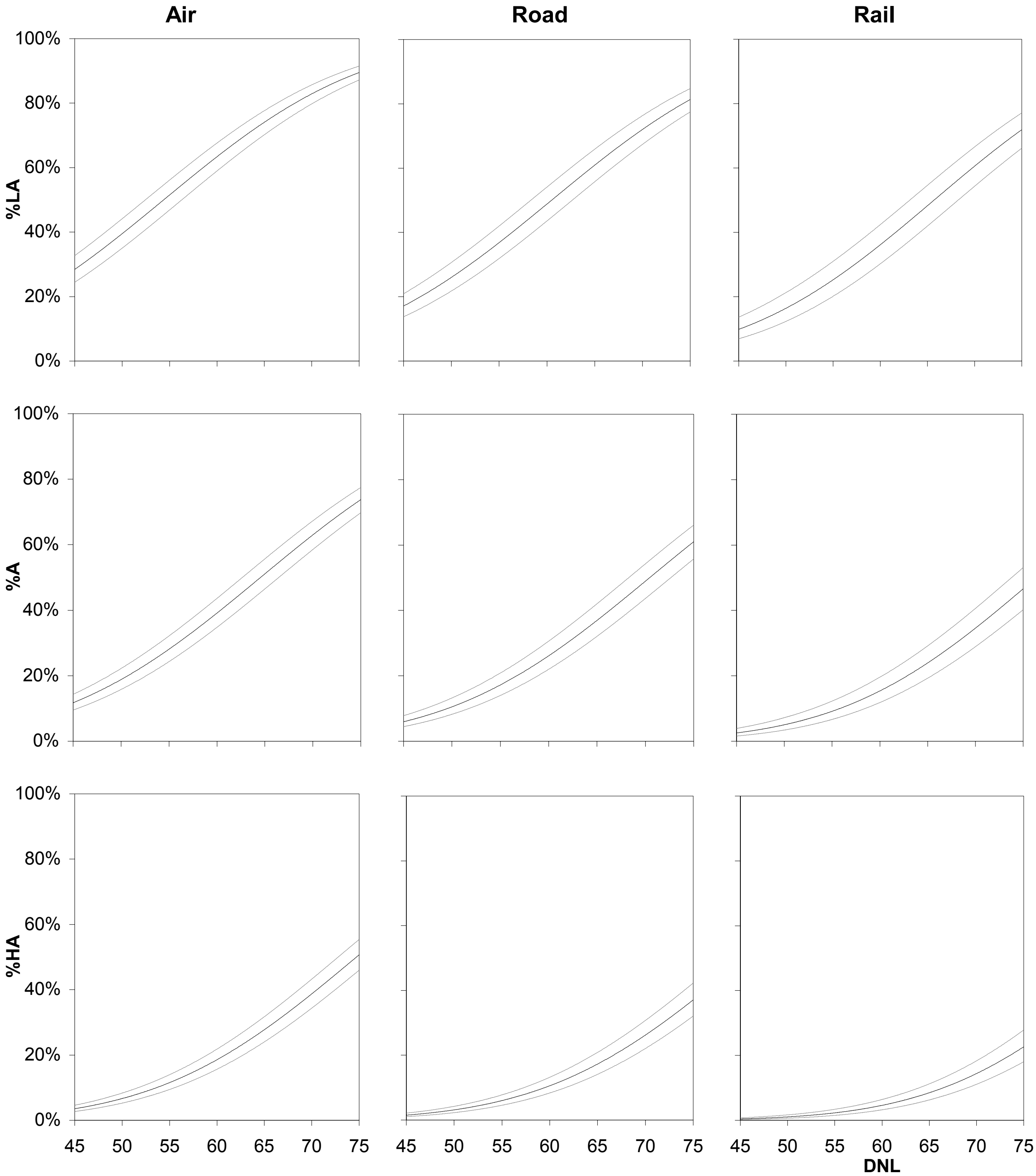


Figure 2: For aircraft, road traffic and railways *%LA* (upper row), *%A* (middle row) and *%HA* (lower row) as a function of *DENL*, together with the 95% confidence intervals. The curves were found by fitting model (4.3) to the data from field surveys (see table 2). The estimates of the parameters are given in table 4.

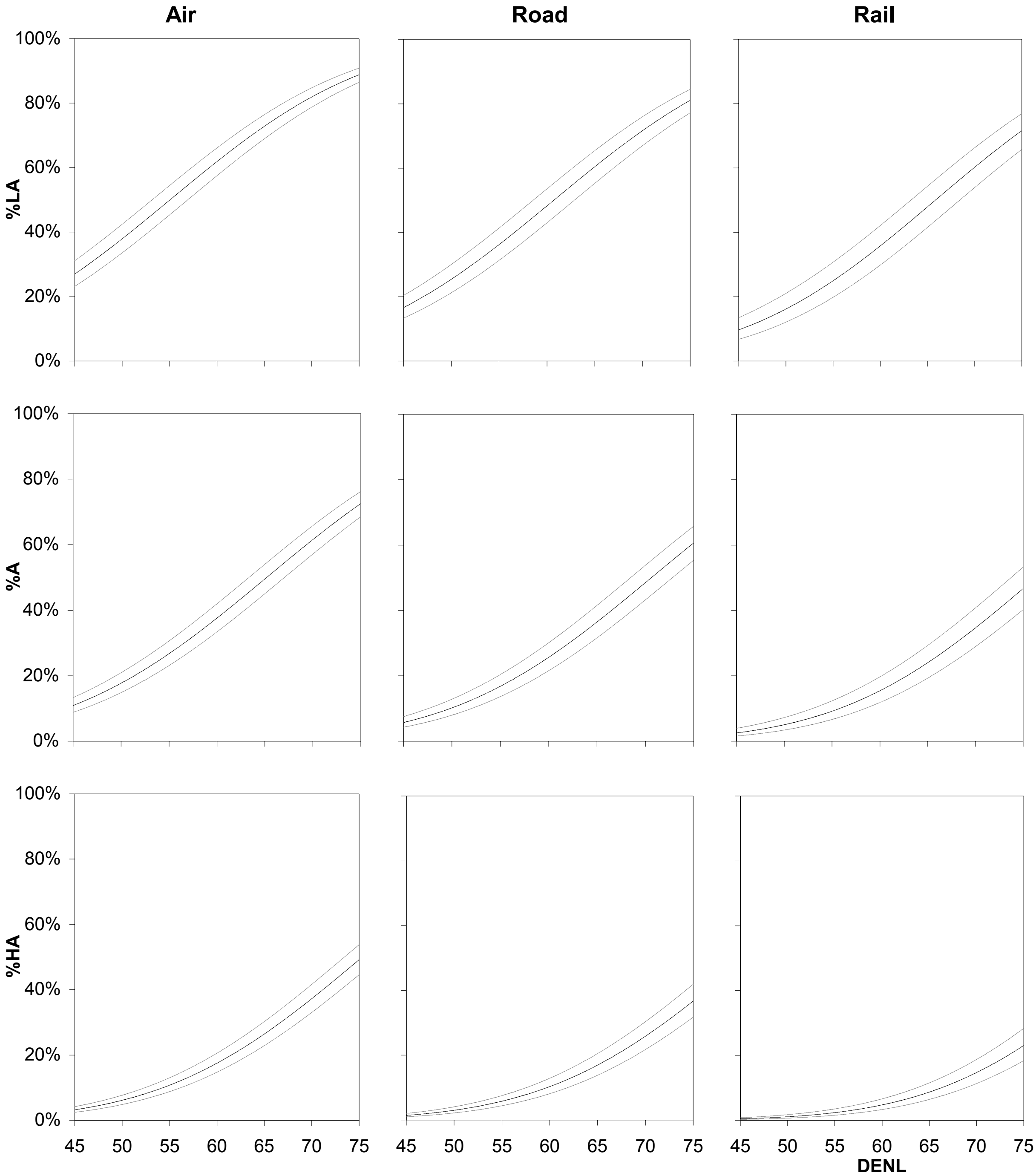


Figure 3: The estimated curves (solid lines) and their polynomial approximations (dashed lines) for *DNL*.

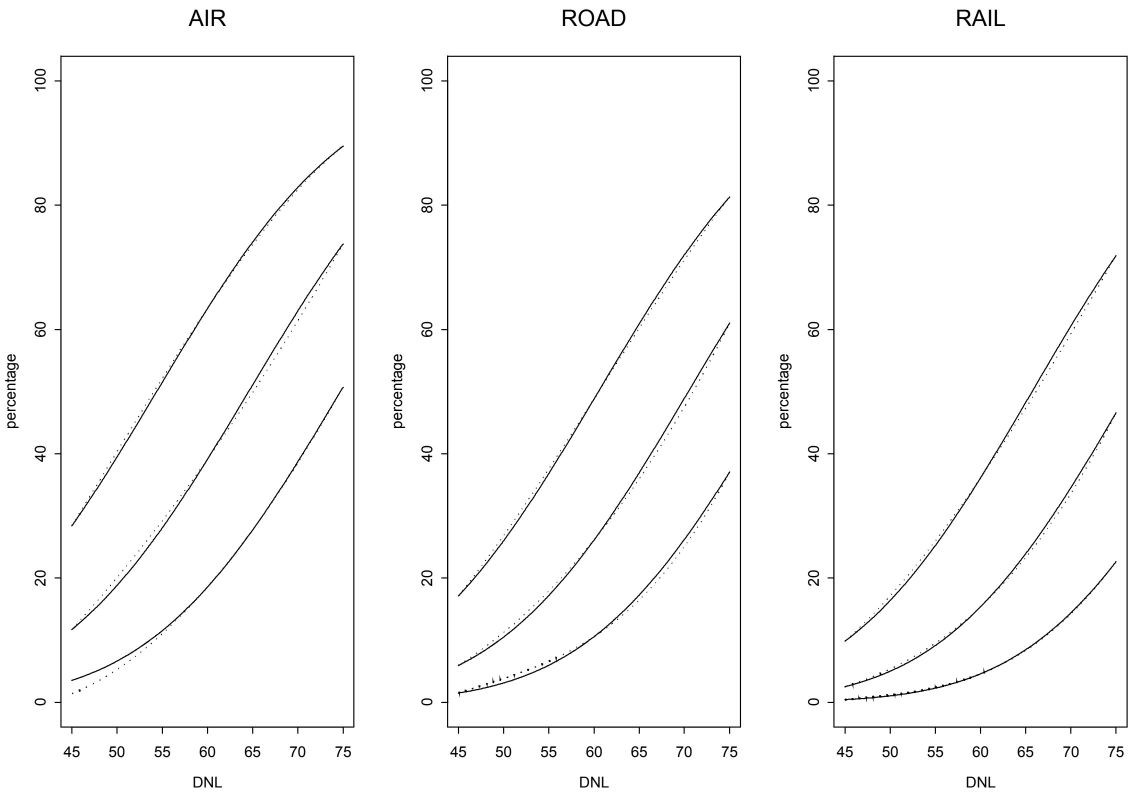
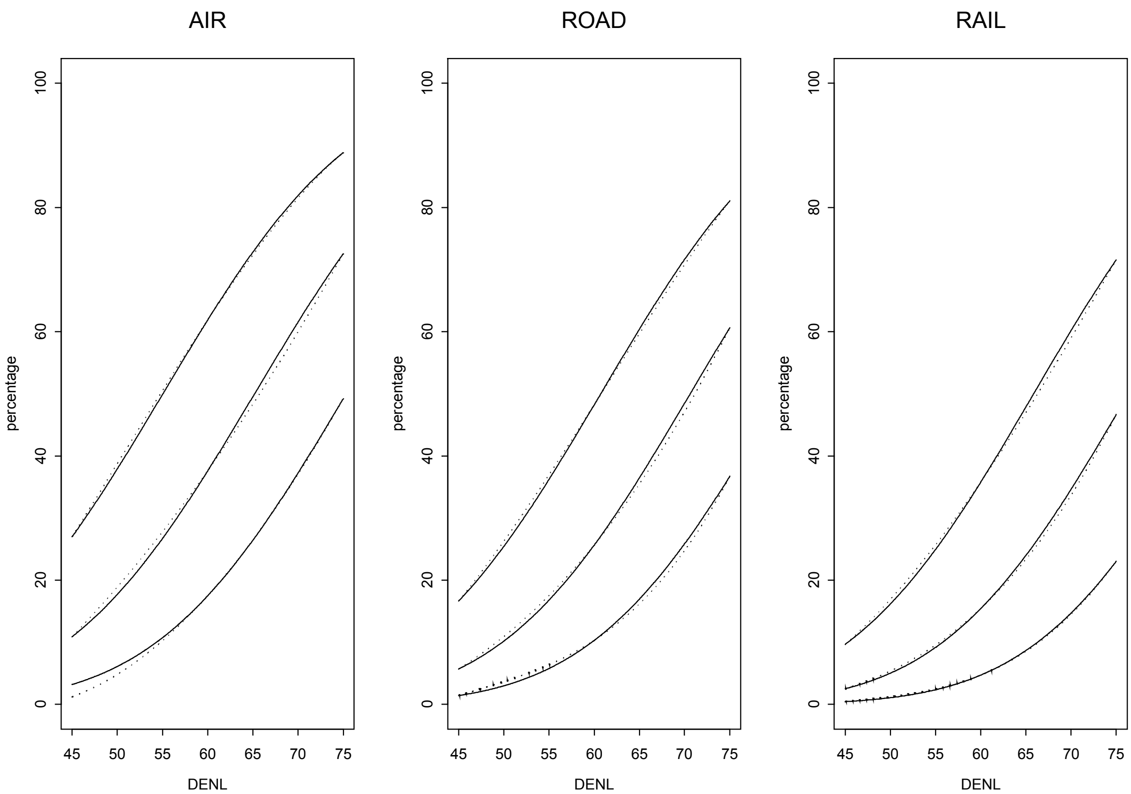



Figure 4: The estimated curves (solid lines) and their polynomial approximations (dashed lines) for *DENL*



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