Dose-response curves for satisfactory sound insulation between dwellings

Jens Holger Rindel[1], Anders Løvstad[1], Ronny Klæboe[2]

[1] Multiconsult, Oslo, Norway
[2] Institute of Transport Economics, Oslo, Norway

Corresponding author's e-mail address: jens.holger.rindel@multiconsult.no

ABSTRACT

A socio-acoustic survey in Norway included field measurements of sound insulation in 600 dwellings, whose residents received a survey to evaluate of the sound quality subjectively. The dwellings were mainly apartments in multi-unit houses. The questionnaire followed ISO/TS 15666 using a five-step verbal evaluation of the degree of annoyance. By means of logit analysis, dose-response curves were derived for airborne and impact sound insulation between dwellings. Both the normal frequency range down to 100 Hz and the extended frequency range down to 50 Hz were evaluated. For airborne sound insulation, the inclusion of low frequencies did improve the correlation in relation to music with bass and drums, but not in relation to speech sounds. For impact sound, the results were strongly in favor of including the low frequencies. The findings in this investigation confirm results from the literature pointing at a slope of 4 percentage points per dB in the middle range of the curves. On this basis, generalized dose-response curves for airborne and impact sound insulation are presented.

INTRODUCTION

In 2015 a social survey of noise conditions in dwellings was carried through in Norway [1]. Measured sound insulation data were collected from newer dwellings, 97 % being apartments in multi-unit houses. Measurements were made between 2002 and 2015. Questionnaires were sent to 3849 persons living at the actual addresses and 702 completed questionnaires were received.

Airborne and impact sound insulation was measured between dwellings in horizontal and vertical direction. From the measured data it was possible to derive both normalized and standardized single-number results, without or with the low-frequency spectrum adaptation terms [2, 3].

The questions used in social surveys on noise problems are very important for the quality of the results. The way in which such questions are asked, and the wording of the possible answers should follow the recommendations in ISO/TS 15666 [4]. The standard also contains an Annex B with the recommended wordings in several other languages, including Norwegian as used in this investigation. The questions and possible answers are of this form: “Thinking about the last 12 month, when you are at home, how much are you annoyed of noise from … ? Not at all – Slightly – Moderately – Very – Extremely “. The answer “Not relevant” was also possible.

Here we shall focus on the results of three questions concerning:

- Speech, TV, computer game, etc. through floor/wall against neighbor
- Loud music with bass and drums through floor/wall against neighbor
- Footfall noise from neighbor living upstairs: walking, running, jumping, moving furniture, impact and strikes against floor etc.

MEASURED SOUND INSULATION AND DEGREE OF ANNOYANCE

Annoyance due to noise from neighbors

For each of the three questions - annoyance from speech, music or impact sound – the average cumulative proportion of annoyance related to the mean values of the measured sound insulation is displayed in Figure 1.

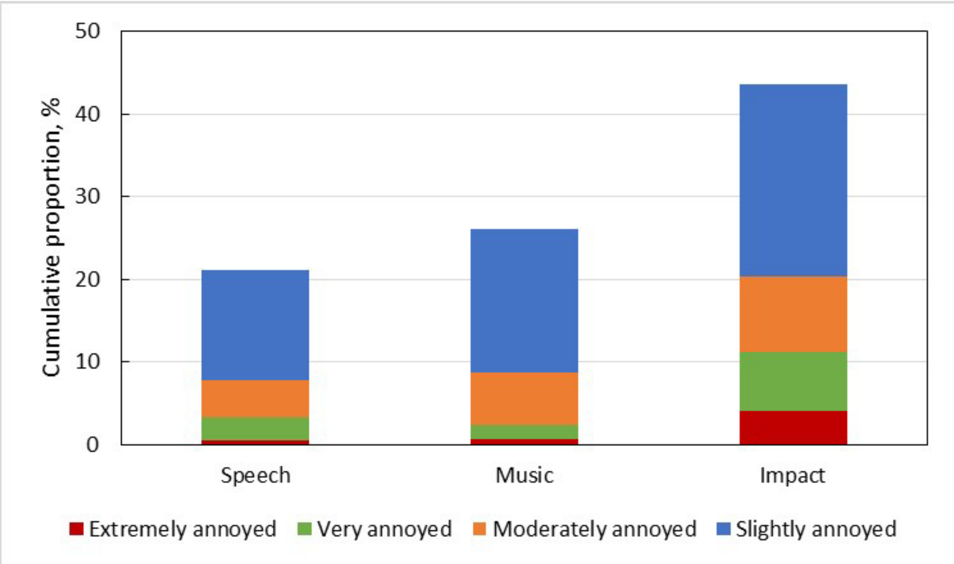

Figure 1: Cumulative proportion of annoyance due to speech, music and impact sound related to the mean value of measured sound insulation.

This shows clearly that impact sound is the biggest problem, and annoyance from speech is less than annoyance from music. We should note that the annoyance rating has nothing to do with how often the various noise events occur. Probably sound from speech, TV etc. occurs much more frequent than sound from loud music with bass and drums; still the latter is rated as more annoying. More results from this investigation is found in ref. [5].

Airborne sound insulation

The main data and results for airborne sound insulation are collected in Table 1. Four different single-number quantities (SNQ) are evaluated from the measured results; the weighted apparent sound reduction index R'_{w} and the weighted standardized level difference $D_{nT,w}$, both with the traditional frequency range 100 Hz – 3150 Hz and with extended frequency range down to 50 Hz. Here we use the abbreviated symbols for the SNQs with frequency range extended to 50 Hz; $R'_{w,50} = R'_{w} + C_{50\text{-}3150}$ and $D_{nT,w,50} = D_{nT,w} + C_{50\text{-}3150}$.

Table 1: Data for measured airborne sound insulation and the degree of annoyance due to music related to the mean value of airborne sound insulation.

	Horizontal				Vertical			
	R'_{w}	$R'_{w,50}$	$D_{nT,w}$	$D_{nT,w,50}$	R'_{w}	$R'_{w,50}$	$D_{nT,w}$	$D_{nT,w,50}$
Measurements								
Number, *N*	355	346	296	296	394	354	366	349
Min, dB	46	45	45	44	50	50	52	51
Max, dB	64	63	65	64	69	68	70	69
Mean, dB	56,8	53,8	58,6	55,4	61,6	58,7	61,0	57,8
Standard dev, dB	3,0	2,8	4,0	3,0	4,3	2,6	4,2	2,4
Speech								
Slightly annoyed	19,9 %	20,1 %	20,0 %	19,9 %	22,7 %	22,0 %	21,9 %	21,8 %
Moderately annoyed	6,8 %	6,9 %	6,8 %	6,7 %	9,2 %	9,3 %	8,3 %	8,9 %
Very annoyed	2,8 %	2,9 %	3,2 %	3,2 %	3,6 %	4,0 %	3,7 %	4,0 %
Extremely annoyed	0,3 %	0,3 %	0,3 %	0,3 %	0,5 %	0,6 %	0,5 %	0,6 %
Music								
Slightly annoyed	27,8 %	26,4 %	25,4 %	24,8 %	27,3 %	25,4 %	25,4 %	26,5 %
Moderately annoyed	8,5 %	8,2 %	7,6 %	7,4 %	9,4 %	9,2 %	9,3 %	9,6 %
Very annoyed	1,8 %	1,7 %	1,8 %	1,8 %	3,2 %	2,8 %	3,0 %	2,9 %
Extremely annoyed	0,5 %	0,5 %	0,6 %	0,6 %	0,7 %	0,8 %	0,8 %	0,9 %

The upper part of Table 1 shows the number of measurements, the range of variation, the mean value and the standard deviation. The middle part of the table shows the results for speech, and the lower part of the table shows the results derived for music with bass and drums, presented as the estimated results for mean value of the sound insulation parameter. NB: The cumulative proportions are stated. The row labelled ‘Slightly annoyed’ is the percentage slightly + moderately + very + extremely annoyed, the row labelled ‘Moderately annoyed’ is the percentage moderately + very + extremely annoyed, and so on.

It is noted that the cumulative proportions are nearly the same in all columns, independently of which acoustic descriptor is used. It is also noted that airborne sound insulation is generally better in vertical direction than in horizontal direction; mean values of R'_{w} and $R'_{w,50}$ are about 5 dB better for floors than for walls. This suggests that annoyance from speech or music should be related mostly to the horizontal sound insulation. If this is correct, it means that the dose-response results for airborne sound insulation in the vertical direction cannot be reliable. In the subjective response from the questionnaire, there is no distinction between horizontal or vertical direction of the annoying sound.

The degree of annoyance from speech is less than that from music. It is also noted that the annoyance from speech seems to be higher in vertical direction than in horizontal direction. However, this is simply a consequence of the fact, that the average sound insulation of the floors is about 5 dB better than that of the walls. Once again, the subjective response cannot distinguish between horizontal and vertical direction of the annoying sound. For airborne sound insulation equal to the mean value there are on average 26 % annoyed (slightly + moderately + very + extremely) by music and 21 % annoyed by speech.

Impact sound insulation

The main data and results for impact sound insulation are collected in Table 2. Four different SNQs were calculated from the measured impact sound insulation, either normalized or standardized, and with or without the 50 Hz spectrum adaptation term. Here we use the abbreviated symbols $L'_{n,w,50} = L'_{n,w} + C_{I,50\text{-}2500}$ and $L'_{nT,w,50} = L'_{nT,w} + C_{I,50\text{-}2500}$. The mean values of the acoustic descriptors show that standardized values are 4 dB lower than normalized values, which is explained by the mean room volume. It is noted that the cumulative proportions are nearly the same in all columns, independently of which acoustic descriptor is used. For impact sound insulation equal to the mean value there are on average 44 % annoyed (slightly + moderately + very + extremely).

Table 2: Data for measured impact sound insulation and the degree of annoyance due to impact sound related to the mean value of impact sound insulation.

	$L'_{n,w}$	$L'_{n,w,50}$	$L'_{nT,w}$	$L'_{nT,w,50}$
Measurements				
Number, *N*	473	439	411	402
Min, dB	41	44	38	40
Max, dB	60	61	56	57
Mean, dB	49,4	53,7	45,4	50,1
Standard dev, dB	4,1	3,0	5,0	2,0
Footfall noise				
Slightly annoyed	45,5 %	42,6 %	43,3 %	42,8 %
Moderately annoyed	22,2 %	19,9 %	20,0 %	19,1 %
Very annoyed	12,3 %	11,2 %	11,2 %	10,2 %
Extremely annoyed	4,5 %	3,8 %	4,3 %	3,8 %

Another important observation from Table 2 is the difference with and without the $C_{I,50\text{-}2500}$ spectrum adaptation term, which is 4 to 5 dB. This is a strong indication that many of the floors in this investigation have problems at low frequencies. This may also be the reason, that the statistical analysis showed no correlation between subjective evaluation and the two SNQs $L'_{n,w}$ and $L'_{nT,w}$ that do not include the low frequencies.

Logistic regression models

The relationships between single-number quantities (SNQ) of sound insulation and annoyance responses were estimated by using ordinal logit models. For evaluation of the goodness of fit of the ordinal logit models, Nagelkerke's R^2 was calculated. These results for each of the four airborne sound insulation SNQs, horizontal or vertical, speech or music are displayed in Figure 2. The goodness of fit is clearly better for music than for speech, and clearly better for horizontal direction compared to vertical direction. However, comparing the four SNQs for music and horizontal direction, $R'_{w,50}$ is slightly better than the others, but there is no significant difference. These results confirm the previous observation, that airborne sound insulation in mainly characterized by the walls (horizontal direction), whereas the floors are in general so much better than the walls, that the vertical direction is of minor importance.

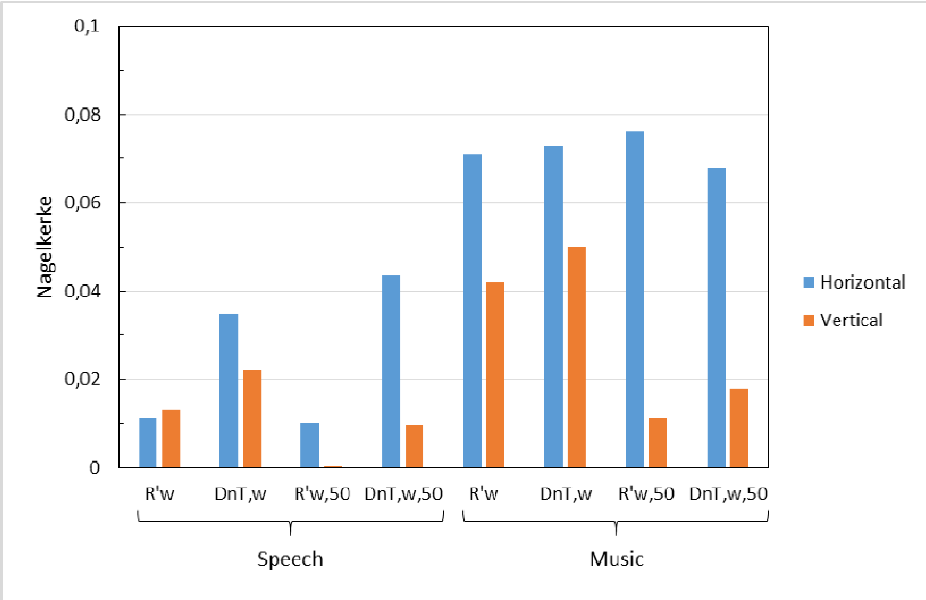

Figure 2: The pseudo R^2 (Nagelkerke) for four different measures of airborne sound insulation in either vertical or horizontal direction, and the correlation with the annoyance due to either speech or music.

For impact sound insulation the goodness of fit is very low for $L'_{n,w}$ and $L'_{nT,w}$; Nagelkerke's R^2 = 0,0003 and 0,0005, respectively. However, including the low frequencies changes the goodness of fit to 0,052 for $L'_{n,w,50}$ and 0,083 for $L'_{nT,w,50}$, i.e. comparable to those obtained for airborne sound insulation in horizontal direction with music.

DOSE-RESONSE CURVES

Airborne sound insulation

Figures 3 and 4 show the dose-response curves obtained from the ordinal logit analyses of the question about annoyance due to music with bass and drums in relation to $R'_{w,50}$ and $D_{nT,w,50}$, respectively.

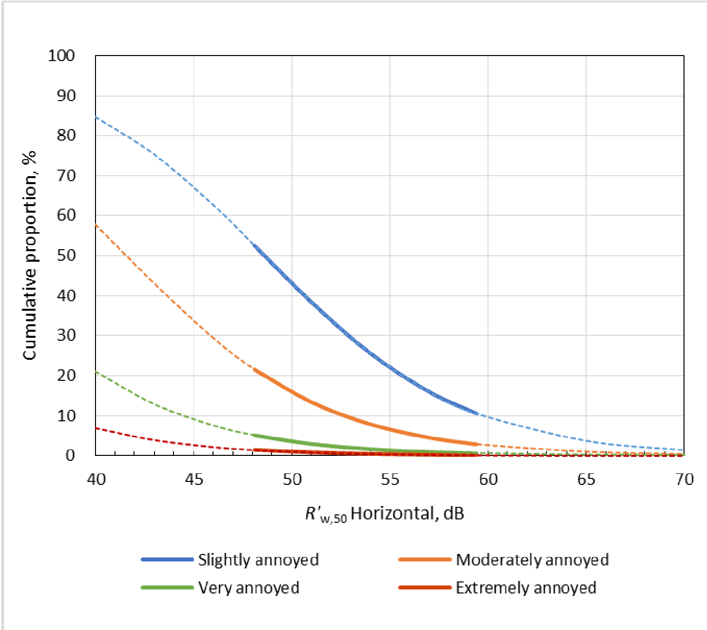

Figure 3: Cumulative proportion of annoyance due to music with bass and drums, as function of airborne sound insulation $R'_{w,50}$ in horizontal direction. Solid lines are within 95 % of the range of measured data.

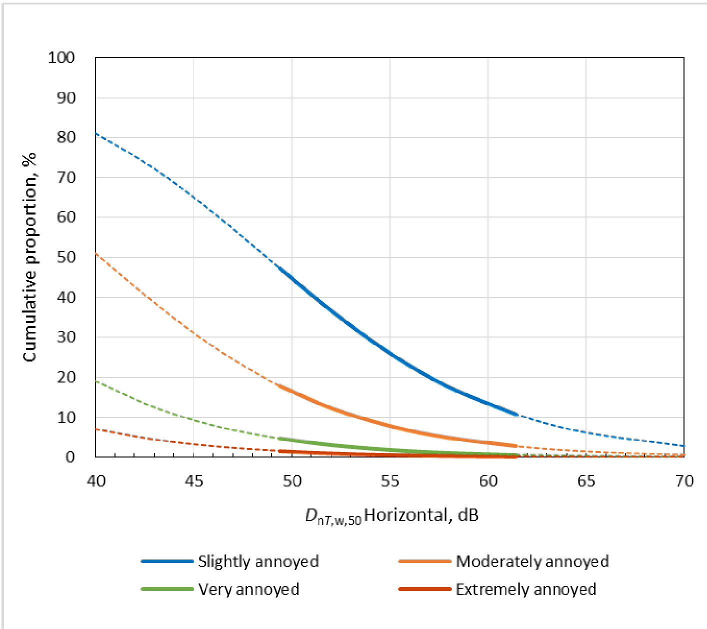

Figure 4: Cumulative proportion of annoyance due to music with bass and drums, as function of airborne sound insulation $D_{nT,w,50}$ in horizontal direction. Solid lines are within 95 % of the range of measured data.

The curves shall be understood so, that the upper curve labeled 'Slightly annoyed' displays the percentage who have answered 'Slightly' + 'Moderately' + 'Very' + 'Extremely' annoyed, and similarly for the other curves.

Impact sound insulation

Figures 5 and 6 show the dose-response curves obtained from the ordinal logit analyses of the question about footfall noise in relation to $L'_{n,w,50}$ and $L'_{nT,w,50}$, respectively.

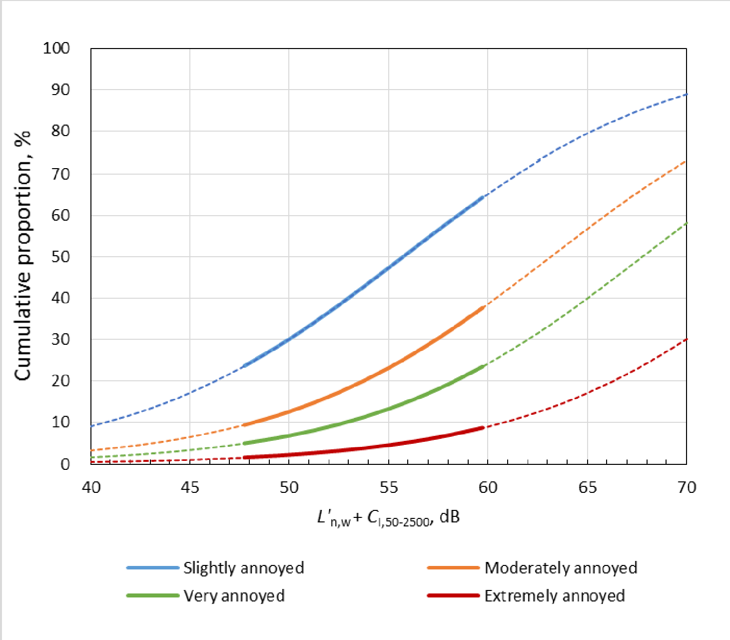

Figure 5: Cumulative proportion of annoyance due to footfall noise, as function of impact sound insulation $L'_{n,w,50}$ in vertical direction. Solid lines are within 95 % of the range of measured data.

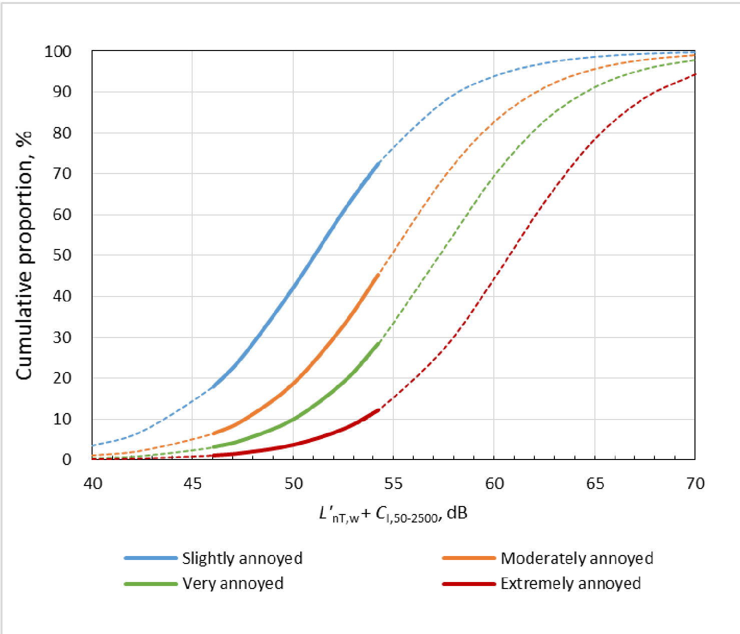

Figure 6: Cumulative proportion of annoyance due to footfall noise, as function of impact sound insulation $L'_{nT,w,50}$ in vertical direction. Solid lines are within 95 % of the range of measured data.

Slope of dose-response curves

The curves in Figures 3 to 6 are sigmoid and in each diagram the shape of the curves is identical; they are only shifted along the abscissa. However, reading the curves in direction of the ordinate, they may seem to have different slopes This is because the slope is flat near the extremes and relatively steep in the middle range. As a simple way to characterize the middle range slope we define this as the slope between 30 % and 70 %. Then we can compare the mid-range slope with the goodness of fit and make the display in Figure 7.

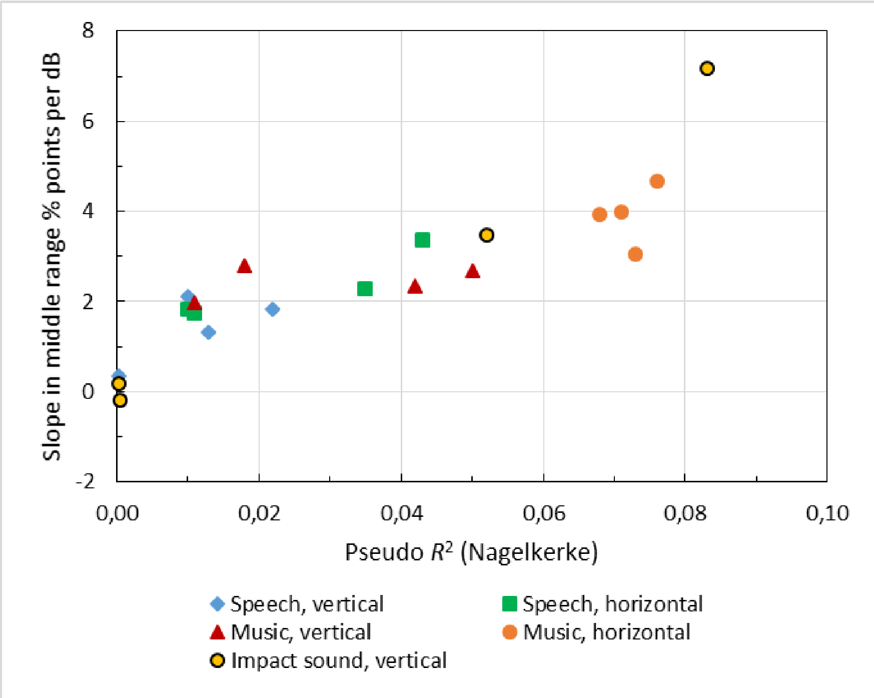

Figure 7: The relation between mid-range slope of dose-response curves and the pseudo R^2 of the logit analysis. Shown for speech and music, horizontal and vertical direction, and for impact sound (opposite sign of slope). There are four SNQs in each group with same symbol.

It is interesting to note that the results with a poor correlation have lower slope than those with better correlation. For instance, the impact SNQs without the 50 Hz adaptation term and the airborne sound insulation evaluated for speech in vertical direction have very poor correlation and a slope below 2 % points per dB. The airborne sound insulation evaluated for music in the horizontal direction has better correlation and the slopes are around 4 % point per dB.

The very steep curves for $L'_{nT,w,50}$ in Figure 6 are quite extreme and hard to understand. The data behind the curves are the same as in Figure 5, except for a correction for volume of receiving room. Comparing Figures 5 and 6, it seems that the data points in Figure 6 have been squeezed together and the standard deviation of the measured data is only 2,0 dB. This means that the spread of data used for this analysis may not be sufficient and for this reason, the slope of the curves may not be reliable.

In previous socio-acoustic investigations, the simple linear regression analysis has sometimes been used. This may be a sufficient approximate model as long as the data are in the middle range of the sigmoid dose-response curve, i.e. between 20 % and 80 %. An analysis of several socio-acoustic investigations on sound insulation [6] concluded that the slope of dose-response curves in the middle range is approximately 4 % points per dB if the correlation coefficient of the linear regression is higher than 0.7. This was found both for airborne and impact sound insulation. The same approximate slope was found for annoyance due to road traffic noise and noise from HVAC heard inside a dwelling [6]. The present investigation seems the support the idea, that ideal dose-response curves for sound insulation should have a mid-range slope of 4 % points per dB.

Generalized dose-response curves

In socio-acoustic investigations of environmental noise there is a tradition for looking at the percentage highly annoyed people. If we define this as the percentage ‘extremely’ + ‘very’ annoyed, the results from the present investigation are below 5 % for airborne sound insulation and below 25 % for impact sound insulation. This is near the extremes where the sigmoid curves are very flat, and it is very difficult to read which dB value corresponds to a certain percentage highly annoyed. Instead, it is suggested to look at the percentage ‘satisfied’, here defined as not annoyed to any degree: 100 % minus percentage ‘extremely’ + ‘very’ + ‘moderately’ + ‘slightly’ annoyed. This has the great advantage that the typical range of sound insulation between dwellings correspond to a portion of the curve with high steepness, thus allowing a more accurate reading of the dose-response relationship.

Examples of this are shown in Figure 8. At the same time, some of the curves have been slightly modified in order to make the mid-range slope equal to the suggested ideal of 4 % points per dB. This means that the dose-response curves may be more generally applicable, as they are not so closely connected to the actual data in a single investigation.

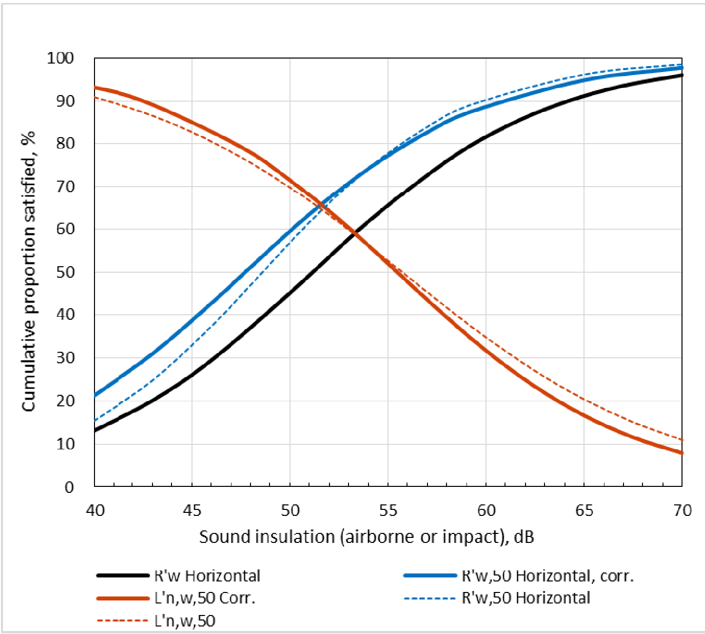

Figure 8: Cumulative proportion of satisfaction with sound insulation (airborne or impact). Dotted lines are the original dose-response curves and solid lines are adjusted to a mid-range slope of 4 % points per dB.

The curve for R'_w in Figure 8 is not adjusted since the mid-range slope is exactly 4,0 % points per dB. The other two curves for $R'_{w,50}$ and $L'_{n,w,50}$ have been slightly adjusted, and the original curves are shown as dotted lines for comparison.

In this investigation the difference between R'_w and $R'_{w,50}$ is found to be 3 dB, which is more than the 2 dB usually found for heavy constructions with sufficient sound insulation at low frequencies [7]. In the present investigation about half of the constructions were light-weight. For the purpose of defining minimum requirements for sound insulation, a difference of only 2 dB should be applied, i.e. requirement ($R'_{w,50}$) = requirement (R'_w) – 2 dB.

It is generally agreed that sound insulation between dwellings shall be satisfactory. If we understand 'satisfactory' to mean at least 80 % satisfied, it follows that the requirements should be $R'_w \geq 59$ dB or $R'_{w,50} \geq 57$ dB and $L'_{n,w,50} \leq 47$ dB (here in terms of normalized SNQs).

CONCLUSION

The results from a new socio-acoustic survey in Norway indicate that insufficient impact sound insulation at low frequencies is a widespread problem in dwellings. Good results were achieved by logit analysis, especially for airborne sound insulation in horizontal direction in relation to music with bass and drums, and for impact sound with low-frequency spectrum adaptation term. Generalized dose-response curves have been suggested based on the findings in this investigation in combination with other experience from the literature pointing at a mid-range slope of 4 % points per dB.

Acknowledgements

This work was supported by "Direktoratet for byggkvalitet" (DIBK), National Office of Building Technology and Administration, Norway. The initial preparation of the measured data from all the building sites were done by Sigrid Husebø Øygard. Hanne Beate Sundfør at the Institute of Transport Economics assisted with the preparation and analysis of the questionnaire.

REFERENCES

[1] DIBK (2016), *Lydforhold i boliger. Evaluering av byggtekniske krav til lydforhold,* (In Norwegian). Document code 127762-RIA-RAP-001. Direktoratet for byggkvalitet (DIBK), National Office of Building Technology and Administration, Oslo, Norway.

[2] ISO 717-1:2013, *Acoustics - Rating of sound insulation in buildings and of building elements - Part 1: Airborne sound insulation.* Second Edition 1996, Third Edition 2013. Organization for Standardization, Geneva, Switzerland.

[3] ISO 717-2:2013, *Acoustics - Rating of sound insulation in buildings and of building elements - Part 2: Impact sound insulation.* Second Edition 1996, Third Edition 2013. Organization for Standardization, Geneva, Switzerland.

[4] ISO/TS 15666:2003. *Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys.* Organization for Standardization, Geneva, Switzerland.

[5] A. Løvstad, J.H. Rindel, C.O. Høsøien, I. Milford, R. Klæboe (2017). *Perceived sound quality in dwellings in Norway.* Proc. 12th ICBEN Congress on Noise as a Public Health Problem, Zürich, Switzerland.

[6] J.H. Rindel (1999), Acoustic quality and sound insulation between dwellings. *Journal of Building Acoustics*, **5**, 291-301.

[7] K. Hagberg (1996), *Acoustic requirements supported by ISO/DIS 717* (*Ljudkrav med stöd av ISO/DIS 717.* (In Swedish). NKB Committee and Work Reports 1996:02. Nordic Committee on Building Regulations, Helsinki. ISBN 951-53-0781-3.