12th ICBEN Congress on
Noise as a Public Health Problem

A statistical model to predict sound level differences between in- and outdoors

Barbara Locher[1], André Piquerez[2], Manuel Habermacher[3], Martina Ragettli[2,4], Martin Röösli[2,4], Mark Brink[5], Christian Cajochen[6], Nicole Probst-Hensch[2,4], Maria Foraster[2], Jean-Marc Wunderli[1]

[1] Empa, Laboratory for Acoustics/Noise control, Swiss Federal Laboratories for Materials Science and Technology, Dubendorf, Switzerland
[2] Swiss Tropical and Public Health Institute, Basel, Switzerland
[3] n-Sphere AG, Zürich, Switzerland
[4] University of Basel, Basel, Switzerland
[5] Federal Office for the Environment, Bern, Switzerland
[6] Centre for Chronobiology, Psychiatric Hospital of the University of Basel, Basel, Switzerland

Corresponding author's e-mail address: barbara.locher@empa.ch

ABSTRACT

Noise exposure prediction models for health effect studies normally yield free field exposure levels as results. However to assess the noise exposure inside dwellings, an estimate of indoor sound levels is necessary. Typically, a constant difference between outdoor and indoor is assumed, neglecting specific conditions. This is a major cause of uncertainty in indoor noise exposure prediction.

To investigate sound level differences between in- and outdoors 102 interviews were carried out at home in a representative sample of Swiss residents. At this occasion sound recordings were performed outdoors and indoors, in the living room and in the bedroom. Three scenarios – open, tilted and closed window – were recorded during three minutes each. For each situation additional parameters such as the orientation towards the source, floor, room and sound insulation characteristics were collected.

The mean outdoor-indoor sound level differences resulted in 11 dB(A) for open, 17 dB(A) for tilted and 29 dB(A) for closed windows. The most relevant parameters for the outdoor – indoor differences were the position of the window, the type of room and the age of the building.

INTRODUCTION

Noise exposure prediction models that are used in health effect studies normally yield free field exposure levels as results. In these models the sound insulation of buildings is neglected. However, to assess the sound exposure of the inhabitants an estimate of the indoor sound level is necessary. Typically a constant difference in level between outdoor and indoor is assumed. This estimate is very coarse and does not take into account specific conditions of

the dwelling situation, window opening behaviour, and building characteristics. Therefore it is a major cause of uncertainty in the prediction of the “true” noise exposure.
According to studies [1] and [2], for aircraft noise, the calculation of indoor sound levels based on free field values can be estimated for closed windows by subtracting 25 dB and for tilted, i.e., slightly open windows by subtracting 15 dB. The difference of 15 dB can also be found in the VDI 2719 (actually as evaluated sound reduction index R_w) and measurements of the DLR-Institut für Luft- und Raumfahrtmedizin [3, 4]. Kötz mentioned in [5] that an unsuitable correction summand for tilted windows can result in a sound level difference discrepancy of 5 dB(A). The DLR did sound level measurements of aircraft and road noise, simultaneously at the facades and the sleeper’s ear from 1999 until 2003. They reported for road respectively aircraft noise median differences of outdoor and indoor SPL_{ASmax} of 13.4 resp. 10.0 dB(A) for open, 13.7 resp. 15.3 dB(A) for tilted and 27.0 resp. 25.6 dB(A) for closed windows [3, 4]. Another study found lower values for tilted windows with a mean difference outdoor – indoor of 12 dB(A) [6]. According to the European Environment Agency report [7] open windows usually have an attenuation from 5-10 dB and slightly open windows 10-15 dB. For closed windows no default values are given, as these depend very much on building properties [7]. Pabst [8] gives differences between open and closed windows ranging from 24 to 35 dB(A), for aircraft noise. These measurements also show, that the same window has a different sound level reduction dependent on the airplane type (up to ± 3 dB(A)) [8].

The aim of this study is to determine the mean difference between the sound level outdoors and indoors for open, tilted and closed windows, which is representative for buildings in Switzerland and compare them to the above mentioned results. The most relevant parameters for the outdoors – indoors differences are determined and a statistical model is developed to predict the sound level difference as a function of dwelling and exposure characteristics.

METHODS

Measurements

From the 5’592 respondents of the socio-acoustic survey of SiRENE [9] 102 participants that agreed to be contacted again were visited at home in a follow–up project. At this occasion, interviews and sound level measurements were carried out. This was done by three people between Mai and November 2016. The participants lived mostly nearby heavily used roads. The sound recordings were performed simultaneously outdoors, with the microphone flush mounted in the middle of the outer face of a window, and indoors, if possible in the bedroom at the position of the pillow (sleepers ear). In case the sleeping room was not facing the main source, typically a major road, the measurements were repeated in the living room with the microphone placed in the middle of the room at a height of 1.5 m. Thereby three scenarios were recorded: open, tilted and closed window. Each scenario was measured during three minutes. During the measurements great attention was given to minimize any sound originating from inside the building. Altogether, measurements were carried out in approximately 160 rooms.
For the measurements, outdoors sound level meters type Noise Sentry RT (class II), which logged A-weighted 1s-L_{eq} levels, were used. To take into account reflections on the window surface the 1s-L_{eq} noise exposure levels are corrected by -5 dB in order to represent a measurement in the open window, the latter being the determinant receiver location for assessment as defined by the Swiss Noise Abatement Ordinance (NAO) [10]. The correction of -5 dB was derived in [11] based on measurements. The correction of 5 dB instead of 6 dB, as would be the case in comparison to free field conditions, is explained by additional reflections from the window frame and the connected room behind.
The measurements inside were performed with sound level meters type NTI XL2 (class I).

One-third octave-band spectra from 50 Hz to 10 kHz were recorded with a temporal resolution of one second.
For each recording situation, additional parameters describing the room and sound insulation characteristics were collected. Table 1 shows a complete list of the parameters.

Table 1: Considered parameters

Parameters	Type	Levels	Number of levels
Position of the window	Categorical	Open, tilted, closed	3
Floor level	Continuous	0, 1, 2, …	---
Room type	Categorical	Sleeping room, living room, eat-in kitchen	3
Orientation of the window towards the source	Categorical	frontal, lateral (90°), opposite side	3
Distance to the source	Continuous	Distance in m	---
Position of the microphone inside	Categorical	In a corner, close to a wall, free in the room	3
Distance microphone inside – window	Continuous	Distance in m	---
Material of the window-frame	Categorical	Wood, synthetic material, metal	3
Number of window gaskets	Categorical	0, 1, 2, 3, unknown	5
Condition of window gaskets	Categorical	Good, medium, bad, unknown	4
Number of window glasses	Categorical	Single, double, triple glazing	3
Type of window	Categorical	1 sash, 2 sashes (both can be opened)	2
Type of façade	Categorical	Façade with single windows, band of windows, glass front	3
Number of windows	Continuous	1, 2, 3, …	---
Proportion of glazed area	Continuous	Percentage, relative to the wall area	---
Volume of the room	Categorical	< 15, 15 – 35, 35 – 60, 60 – 150 m^3	4
Type of building	Categorical	single-family house, apartment building, block of flats	3
Age of building	Categorical	> 40, 20 – 40, < 20 years, unknown	4
Aeration	Categorical	Window ventilation, artificial ventilation	2
Room characteristics	Categorical	Corner room, top floor with pitched roof area, other	3

Calculation of the sound level differences between outdoors and indoors

The time was set before every measurement for both instruments (accuracy +/- 2 seconds), but there was no exact time synchronisation between the devices. To estimate the mean difference between the sound pressure level outdoors and indoors the following procedure was carried out: For the approximately three minutes of measurement for each situation and window scenario, an energetically mean sound level was calculated for intervals of 10 seconds. This was primarily done in order to account for a possible slight time offset. For each

10 s L_{Aeq} the difference between outdoors and indoors was calculated. These approximately 18 data points (in 3 minutes) were plotted and a linear fit was applied (Figure 1 shows an example). In order to check if there was a correlation between the sound levels outdoors and indoors R^2 was determined. All situations with an $R^2 \geq 0.45$ were classified as potentially valid measurements. As a second criterion the slope had to be close to 1. For measurements with a slope < 0.5 or > 1.5 it was visually verified if a plausible correlation between in- and outdoors exists. This leads to a general restriction that more often measurements with closed windows, with windows that have a high sound insulation and places with low sound levels outdoors are not considered in the statistical analyses. From the 10s L_{Aeq} $\Delta_{out - in}$ the median was taken as representative difference for the specific situation.

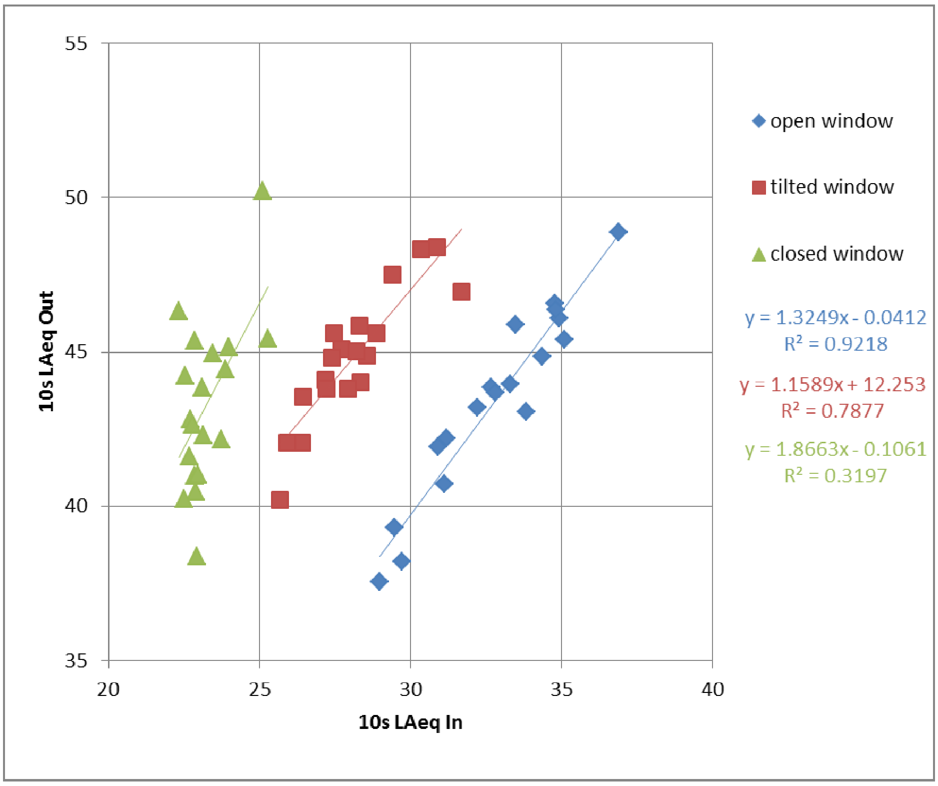

Figure 1: Example of measurement data (ID 0342): 10 s L_{Aeq} outdoors (corrected by – 5dB) versus indoors. In this case the median difference outdoor – indoor for the open (blue) and the tilted window (red) with $R^2 \geq 0.45$ are included in the further analysis. As there is no clear correlation outdoor – indoor for the closed window (green, $R^2 = 0.32$), this measurement is not considered in the statistical analyses.

Statistical analyses

The statistical analyses were carried out with R version 3.1.3. In a first step, a boxplot for each window position was plotted and analysed. Outliers were removed following Tukey's method [12]. Thereby an interquartile range (IQR) of 1.5 was used. The method was applied on each window position separately.

The relation of the different predictors given in Table 1 and the difference of the sound level outdoors - indoors was analysed by means of linear regression models. These models combine categorical variables, continuous variables and interactions to predict the dependent variable (difference L_{Aeq} out - in).

Due to many potential influencing parameters and interactions, open and tilted windows were analysed together and closed windows separately. The variable selection was done by a stepwise approach with the Akaike Information Criteria (AIC), where the model with the lowest AIC was preferred. Variables were considered significant if the probability (p) was ≤ 0.05. Non-significant variables and interactions were excluded from the final model. Compliance with the model assumptions was confirmed by visual inspection of the residual plots.

RESULTS

Sound level differences between outdoors and indoors

From the measurements in 160 rooms, 115 measurements for open, 116 measurements for tilted and 76 measurements for closed windows were valid. The resulting median sound level difference outdoors - indoors for open windows is 11 dB(A) with a standard deviation of 2.9 dB(A). The values range from a minimum of 5 dB(A) to a maximum of 17 dB(A), without considering outliers. For tilted windows the median difference outdoors – indoors is 17 dB(A) with a standard deviation of 2.7 dB(A). The differences range from 11 to 23 dB(A), without outliers. Closed windows result in a median difference outdoors – indoors of 29 dB(A) with a standard deviation of 4.4 dB(A). They exhibit the widest range of values, from a minimal difference of 20 to a maximal difference of 39 dB(A), again without outliers. Figure 2 shows the boxplots for open, tilted and closed windows and

Table 2 tabulates the corresponding values. For the statistical analyses the 6 outliers in the boxplots, defined as outside 1.5 times the interquartile range, were removed.

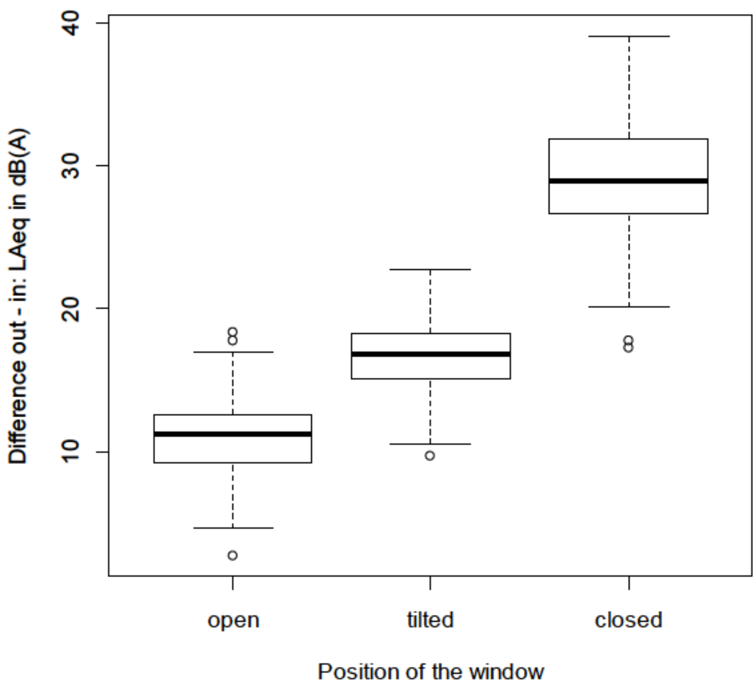

Figure 2: Boxplots showing the median (horizontal line in boxes), the 25% and the 75% quantiles (lower and upper boundaries of boxes), the whiskers comprising the data within 1.5 times the interquartile range, and outliers outside the whiskers.

Table 2: Median of the differences of the sound levels outdoors (corrected by - 5 dB, representing measurement in open window) and indoors for the different window positions.

Window position	Difference of the 10 s L_{Aeq} outdoors and indoors [dB(A)] Median (25%, 75% quantile)	Number of measurements
open	11.0 (9.1, 12.5)	115
tilted	16.8 (15.0, 18.2)	116
closed	28.8 (26.4, 31.8)	76
all		307

Linear regression model for open and tilted windows

For open and tilted windows the analysis of variance (ANOVA) yields four significant parameters: (a) the window position, i.e. open or tilted, ($p < 0.001$), (b) the type of room ($p < 0.001$), (c) the volume of the room ($p = 0.05$) and (d) the age of the building ($p < 0.001$). The position of the window accounted for 57% of the variability in the data. Another 8% of the variance is explained by the room type (5%) and the age of the building (3%). The volume of the room does not account for much of the variability (1%). No significant interactions between the different parameters were detected.
To describe these effects, the following linear model was found to be appropriate:

$$y = \beta_0 + window + room + volume + age \qquad (1)$$

In this equation y is the dependent variable "difference outdoors – indoors", β_0 is the overall mean of this difference, and window, room, volume, and age are fixed effects. The model coefficients are presented in Table 3. This linear model yields an explained variance of 65% (adjusted R^2).

Table 3: Parameter estimates of the regression model for indoor-outdoor sound level differences for open and tilted windows.

Parameter	Symbol in Eq. 1	Coeff.	95% CI	Std. error	t value	Pr (>|t|)
Intercept	β_0	9.6	[8.6;10.6]	0.5	18.5	< 0.001
Window position	window = open	0^a				
	window = tilted	6.1	[5.4;6.7]	0.3	19.3	< 0.001
Room	room = bedroom	0^a				
	room = eat-in kitchen	- 5.1	[-7.3;-2.9]	1.1	- 4.6	< 0.001
	room = living room	- 1.2	[-1.9;-0.5]	0.4	- 3.2	0.002
Room volume	volume = 15 - 35 m^3	0^a				
	volume = 35 - 60 m^3	-0.1	[-0.8;0.5]	0.3	- 0.4	0.679
	volume = 60 -150 m^3	1.1	[0.1;2.1]	0.5	2.1	0.033
Age of building	age < 20 years	0^a				
	age = 20 – 40 years	1.7	[0.7;2.7]	0.5	3.2	0.001
	age > 40 years	1.9	[0.9;2.9]	0.5	3.7	< 0.001

0^a Reference values.

Analyses of closed windows

For the closed windows the analysis of variance (ANOVA) yields two significant parameters: (a) the floor level and (b) the type of window. But the linear model with these two parameters cannot explain much of the variance with an adjusted R^2 of only 0.1. Most of the parameters influencing the sound insulation of a window (number and condition of window gaskets, material of window frame), the percentage of glass, façade type, the volume of the room and also the position of the microphone indoors do not significantly affect the sound level differences between inside and outside.

The main influence on the differences outdoors – indoors is attributed to the mean sound level outdoors with an R^2 of 0.52 (see Figure 3). This result could be explained by an increasing sound insulation standard in dependence of the outside sound exposure, as it is prescribed by the Swiss standard for sound insulation in building constructions [13]. However it has to be assumed that this finding at least partially indicates also a limitation of the measurement concept.

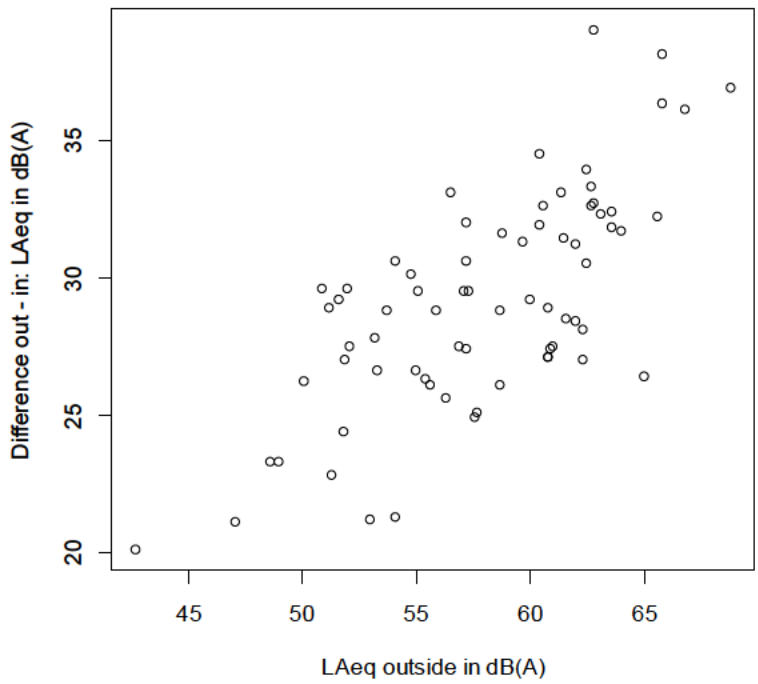

Figure 3: Plot showing the difference outdoors – indoors for measurements with closed windows as a function of the energetically averaged sound level outdoors.

If we include the sound level outdoors as a parameter, despite the mentioned limitation, the following linear model for closed windows can be found:

$$y = \beta_0 + \beta_1 \cdot floor + frame + \beta_2 \cdot glazed\_area + volume + \beta_3 \cdot L_{Aeq}\_outdoors \quad (2)$$

In this equation y is the dependent variable “difference outdoors – indoors”, β_0 is the intercept, the material of the window-frame (*frame*) and the volume of the room (*volume*) are fixed effects, and the floor level (*floor*), the proportion of glazed area relative to the wall area (*glazed_area*) and the L_{Aeq} outdoors are the covariates with the corresponding regression coefficients β_1, β_2 and β_3. The model coefficients are presented in Table 4. This linear model yields an explained variance of 61% (adjusted R^2).

Table 4: Parameter estimates of the regression model for indoor-outdoor sound level differences for closed windows.

Parameter	Symbol	Coeff.	95% CI	Std. error	t value	Pr (>|t|)
Intercept	β_0	-5.55	[-13.8;2.7]	4.12	-1.3	0.18
Floor level	β_1	0.32	[-0.1;0.7]	0.19	1.7	0.1
Material of the window-frame	frame = wood	0 [a]				
	frame = synthetic	2.46	[1.1;3.8]	0.66	3.7	< 0.001
	frame = metal	1.79	[-2.2;5.8]	2.0	0.9	0.37
Proportion of glazed area	β_2	-0.04	[-0.1;0.0]	0.03	-1.7	0.09
Room volume	volume= < 15 m^3	0 [a]				
	volume = 15 - 35 m^3	4.25	[-1.0;9.5]	2.61	1.6	0.11
	volume = 35 - 60 m^3	5.31	[0.1;10.5]	2.61	2.0	0.05
	volume = 60 -150 m^3	4.09	[-1.3;9.5]	2.71	1.5	0.14
Sound level outdoors (L_{Aeq})	β_3	0.52	[0.4;0.6]	0.06	8.7	< 0.001

0 [a] Reference values.

DISCUSSION

In this study over 300 measurements were carried out at people's homes in a representative sample of about 100 Swiss residents. The median differences between sound levels outdoors and indoors are 11 ± 2.9 dB(A) for open, 17 ± 2.7 dB(A) for tilted, and 29 ± 4.4 dB(A) for closed windows. The range from minimal to maximal value without outliers is 12 dB(A) for open and tilted windows, and 19 dB(A) for closed windows. In case of closed windows the sound insulation depends very much on building properties, especially the windows (size of windows, double, triple or special glazing, window gaskets, …). This means that for a specific situation the real difference can deviate significantly from the median difference between the sound level outdoors and indoors, as measured in our sample.

For open and tilted windows, apart from the position of the window, the room type and the age of the building turned out to be highly significant parameters. In bedrooms the differences outdoors – indoors are slightly higher (1 dB) than in living rooms and clearly higher (4.5 dB) than in eat-in kitchens. This can be explained by more absorbing materials in bedrooms (bed, curtains, carpets), which is normally also true for living rooms (sofa, curtains, carpets). Eat-in kitchens generally have more sound-reflecting surfaces. Bigger rooms with the same incoming sound level have a lower sound level inside and therefore a bigger difference outdoors – indoors, which the statistical model shows for rooms with 60 – 150 m^3 (+1.1 dB). The volumes of living rooms and eat-in kitchens are generally bigger than that of sleeping rooms.
The age of the building effect shows the trend that newer buildings have slightly lower differences outdoors – indoors (20 – 40 years: + 1.7 dB, > 40 years: +1.9 dB). This might reflect the bigger window sizes of recently constructed buildings. Relevant in this case is the window size of the open or tilted window and not the number of windows or proportion of glazed area, which do not significantly affect the sound level differences. The distance from the microphone inside to the window does not significantly affect the sound level differences between inside and outside, which supports the assumption of a diffuse sound field.

The statistical analysis for the closed window dataset resulted in a linear model with the floor level, the material of the window frame, the proportion of glazed area and the volume of the room as significant parameters, however with a rather small overall effect. In addition the outside sound pressure level turned out to show a high correlation with the difference outdoors-indoors. On the one hand this can be explained by the fact, that buildings close to noisy streets have more often windows with a high sound insulation, especially in Switzerland where extensive noise mitigation programs have been realized in the past decade. On the other hand Swiss building regulations specify since 30 years a minimal sound insulation in dependence of the outside noise level. Nevertheless it must be assumed, that this strong influence is at least partially also indicating a limitation of the measurement procedure, as high levels of sound insulation cannot be exactly measured with typical levels of outside traffic noise. For that purpose, alternative methods with an artificial source, i.e. a loudspeaker, should be considered. In addition it has to be kept in mind that rooms with high levels of sound insulation are more likely to have been disregarded in the statistical analysis because of a lacking correlation between the sound levels outdoors and indoors. Hence it must be concluded that the dataset for closed windows is prone to be unbalanced with a tendency to underestimate the real difference in level.

The mean values determined in this study are assumed to be representative for road traffic noise and buildings in Switzerland. According to the authors opinion they should also be applicable for other noise sources and other countries with comparable building and construction standards.

Compared to the DLR-study [3, 4], the newest comparable study, the values for tilted and closed windows are about 3 resp. 2 dB(A) higher and for the open window about 2 dB(A) lower. The DLR-study showed practically no difference between the open and tilted window in case of road traffic noise, compared to 6 dB in the present study. If we compare the values with the results for aircraft noise in the DLR-study [3, 4], the differences are 1 dB(A) higher for open windows, 2 dB(A) higher for tilted windows and 3 dB(A) higher for closed windows. Aircraft and road noise have diverse incident angles and slightly different frequency spectra. Furthermore the DLR-study reports differences in the maximum sound pressure levels SPL_{ASmax} and for aircraft noise also in the L_{ASeq_event}. The differences between these two values are with ≤ 0.5 dB rather small. The measurements outdoors were done in 2 m distance from the façade and corrected for free field condition by 3 dB. In the DLR-study all measurements were done in sleeping rooms. In addition there might also be small country-specific differences in the architectural style. It is very likely, that such factors also play a role.

REFERENCES

[1] BUWAL (1998). *Belastungsgrenzwerte für den Lärm der Landesflughäfen.* Bundesamt für Umwelt, Wald und Landschaft, Bern 1998. Schriftenreihe Umwelt Nr. 296.

[2] Jansen, G., Linnemeier, A., Nitzsche, M. (1995). Methodenkritische Überlegungen und Empfehlungen zur Bewertung von Nachtfluglärm. *Zeitschrift für Lärmbekämpfung, 42*, 91-106.

[3] Müller, U. (2006). *Sound level measurement of aircraft and vehicle noise, simultaneously recorded at facades and the sleeper's ear.* Paper presented at the Euronoise 2006, Tampere, Finland.

[4] Basner, M., Müller, U. & Samel, A. (2004). *Nachtfluglärmwirkungen (Band 2): Methodik, Akustik.* DLR-Forschungsbericht 2004-08/D, Institut für Luft- und Raumfahrtmedizin des DLR, Köln, p. 130 S.

[5] Kötz, W.-D. (2004). Zur Frage der effektiven Schalldämmung von geöffneten Fenstern. *Zeitschrift für Lärmbekämpfung, 51*(1), 21-26.

[6] Maschke, C., Volz, R., Jakob, A. & Augustin, E. Pegeldifferenzen gekippt-geöffneter Fenster bei Fluglärm – Messungen nach DIN EN ISO 140-5 Gesamt-Lautsprecher-Verfahren.

[7] EEA (2010). *Good practice guide on noise exposure and potential health effects.* EEA Technical report, No. 11, European Environment Agency, Copenhagen, 2010

[8] Pabst, F. (2009). *Massnahmenkonzept zum Zürcher Flughafen-Index (ZFI).* Projektgruppe „Raumentwicklung/Wohnqualität". Fragenbeantwortung im Rahmen der Studie „Bauqualität und Schalldämmung". Ramser Bauphysik AG, 2009.

[9] Karipidis, I., et al. (2014). *Reconstruction of historical noise exposure data for environmental epidemiology in Switzerland within the SiRENE project.* Noise Mapping, 2014. 1(1).

[10] NAO (1986). *Lärmschutz-Verordnung (LSV) vom 15. Dezember 1986 (Stand am 1. August 2010) (Noise Abatement Ordinance (NAO) from 15 December 1986 (Effective 1 August 2010)). SR 814.41*.

[11] BAFU (2015). *Methode zur Ermittlung der Aussenlärm-Immissionen bei geschlossenem Fenster. Vollzugshilfe zur Lärmschutzverordnung (LSV). Aktualisierung der Mitteilung zur LSV Nr. 7 von 1995.* Bundesamt für Umwelt, Bern 2015. Umwelt-Vollzug Nr. 1502: p. 3 S.

[12] Tukey, J. (1977). *Exploratory data analysis., Bd. 7616 von Behavioral Science: Quantitative Methods*. Addison-Wesley.

[13] SIA 181 (2006). *Schallschutz im Hochbau. Schweizer Norm SN 520 181.*