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Validation of the exposure modelling within SiRENE by long-term measurements

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ABSTRACT

In the SiRENE (Short and Long Term Effects of Transportation Noise Exposure) project, a nationwide assessment of road, railway and aircraft noise exposure was conducted for the year 2011. Noise exposure was thereby modelled at façade points of all residential buildings in Switzerland. Based on a stratified sample, a socio-acoustic survey with 5592 respondents was performed. In the follow-up project SIAS, 102 of these participants volunteered in 2016 to temporally equip their sleeping- and / or living room windows with sound level meters, resulting in 180 validation cases of the SiRENE exposure modelling. The sound level meters were flush mounted on the outer face of the closed window and recorded A-weighted equivalent sound pressure levels in a temporal resolution of 1 s during approximately one week. With the address and floor information of each participant, the corresponding point on the façade of the SiRENE – database was assigned. Comparisons revealed on average 1.5 ± 5 dB(A) higher calculated than measured L_{DEN}. After removing situations with recently installed noise mitigation measures and strong building influences the overestimation however reduced to 0.4 ± 4 dB(A). It can therefore be concluded that the exposure modelling on average yields an accurate representation of the real exposure situation.

INTRODUCTION

Transportation noise is one of the main sources of noise pollution. In the SiRENE project (Short and Long Term Effects of Transportation Noise Exposure) a nationwide assessment of road traffic, railway and aircraft noise was conducted for the year 2011. A maximum of 3 façade points, spaced by a minimum distance of 5 meters, were specified for each façade and floor of all buildings, resulting in a total of 54,300,000 façade points, assigned to 1,813,000 buildings throughout Switzerland [1]. Based on the noise calculations, conclusions on acute, short and long-term effects of noise, on annoyance, sleep disturbance as well as cardio-metabolic health outcomes were derived [2-5]. In this follow-up study a validation of the exposure modeling based on long-term measurements was performed.

Road traffic noise modelling within SiRENE

The measurement sites were mainly exposed to road traffic noise. Therefore the focus of the following section is on road traffic noise modeling within SiRENE. However the comparison with measurements was conducted with the modelled total traffic noise (road, airplane and railway combined), as the measurements automatically capture all noise sources. Within the SiRENE Model, the road and building geometry was based on the VECTOR25 dataset by swisstopo [6]. Additionally to the spatial data further information about the road sections like slope, road classification and width, pavement type, speed limit and traffic statistics were used [1]. Information on noise barriers was obtained from the Federal Road Office (FEDRO) and cantonal offices for infrastructure and traffic. Traffic information was gathered using the sophisticated traffic model by Arendt Consulting [7, 8]. This model links annual traffic information provided by monitoring systems of the federal department of the environment, transport and energy DETEC with population census data. This model allows determining traffic information also for street sections, which are not covered by traffic counting stations. Traffic speed and the ratio of heavy traffic are also taken from the model. To calculate the road emission, the sonROAD emission model was used [9]. Noise propagation was calculated using StL-86 [10].

METHOD

From the 5'592 respondents of the socio-acoustic survey of SiRENE, 102 participants that agreed to be contacted again were visited at home in the follow–up project SIAS. They volunteered to equip their sleeping- and / or living room windows with sound level meters during approximately one week. The sound level meters (Type: noise sentry RT, a class II measurement device with measurement uncertainty of about 1 dB(A)) were flush mounted on the outer face of a closed window. The sound level meters logged 1s-Leq levels during the measurement period. Afterwards the participants removed the sound level meters and sent them back by mail. To take into account reflections on the window surface the 1s-Leq noise exposure levels were corrected by -5 dB(A), 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) [11]. The correction of -5 dB was derived in [12, 13] 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. The dataset was aggregated to 1h-Leq's, resulting in 24 values per day for typically 7 days of measurement.

Data analysis and cleansing

The participants were instructed to journalize dominant noise sources other than traffic noise during the measurement period in a questionnaire. Such time periods with disturbing noises were identified and removed from the dataset. Seven dwellings were close to churches. In these situations bell tolling around every full hour and additional events with dominant ringing were removed. In addition, an outlier detection following Tukey's method [14] was applied to account for further disturbing noise events not journalized by the participants. Thereby an IQR (Inter Quartile Range) of 1.5 was used according to Equations (1) and (2). The method was applied on each of the 24 1h-Leq's of the measurement period.

$$x_{out,upper,h} > q_{75\%,h} + 1.5 \cdot \left(q_{75\%,h} - q_{25\%,h}\right) \tag{1}$$

$$x_{out,lower,h} < q_{25\%,h} - 1.5 \cdot \left(q_{75\%,h} - q_{25\%,h}\right) \tag{2}$$

With:

$q_{75\%,h}$	75 -% Quantile of every 1h-Leq of all weekdays
$q_{75\%,h}$	25 -% Quantile of every 1h-Leq of all weekdays
$x_{out,upper,h}$	Upper outliers for every 1h-Leq of all weekdays
$x_{out,lower,h}$	Lower outliers for every 1h-Leq of all weekdays

Based on the outlier-corrected 1h-Leq levels, the noise exposure levels Leq_{07-23}, Leq_{19-23} and Leq_{23-07} were calculated. From these levels the noise exposure L_{DEN} was calculated as follows:

$$L_{DEN} = 10 \cdot \log_{10}\left(\left[\frac{12}{24} \cdot 10^{Leq_d/10} + \frac{4}{24} \cdot 10^{(Leq_e+5)/10} + \frac{8}{24} \cdot 10^{(Leq_n+10)/10}\right]\right) \tag{3}$$

With

Leq_d	Mean A-weighted noise exposure level during day (07-19 h)
Leq_e	Mean A- weighted noise exposure level during evening (19-23 h)
Leq_n	Mean A- weighted noise exposure level during night (23-07 h)

To enable a comparison between the modelled façade points of the SiRENE-project and the measurements, each measurement site was manually assigned to a façade point from the SiRENE exposure database. The distribution of façade points was generated based on the building outlines from the digital landscape model of Switzerland (VECTOR25, swisstopo [6]) dating from 1998 – 2006. Some of the participants had moved to recently built houses, which did not exist in the landscape model and had thus not been modelled in SiRENE. In other situations windows led to courtyards, which had not been considered in the modelling. Consequently at these sites no calculation results were available and hence no comparison between measured and simulated levels was possible. Therefore these measurements were removed for the comparison.

A few measurements with faulty acoustic data (permanent disturbing noises, damaged sound level meters or corrupt data) were also removed from the analysis.

Some of the measuring devices had unfortunately been placed on the window ledge. Those measurements are likely to exhibit a reduced exposition to traffic noise sources, especially for upper floors. As a consequence, these measurements were also omitted for the analysis.

As mentioned before, the measurements were performed on the outer window surface of living/sleeping rooms. In some cases the participants used closed window shutters. Based on the measurement log, the timeframe with closed shutters were differentiated into three categories: Closed shutters during nighttime, during daytime or all the time. As closed window shutters cause significant additional shielding, such recordings were removed from the dataset, however only for the timeframes with closed conditions.

Table 1 gives an overview of the reason and the number of excluded measurements in the data cleansing process. After removing all unusable measurements, 113 to 140 (depending on the timeframe) datasets from the original 180 measurements remained for comparison with the modelled SiRENE noise exposure levels.

Table 1: Number of validation cases and reasons for exclusion. Highlighted in orange are validation cases, which were removed because of propagation conditions not considered in the modelling.

	L_{DEN}	L_{07-19}	L_{19-23}	L_{23-07}
Full dataset	**180**	**180**	**180**	**180**
Missing data (No facade points, faulty acoustic data, no measurement protocol …)	20	20	20	20
Noise Sentry flush mounted to window ledge	11	11	11	11
Closed shutters during nighttime	27	0	0	27
Closed shutters during daytime	1	1	1	0
Closed shutters all the time	8	8	8	8
Total removed measurements	67	40	40	66
Corrected dataset after data cleansing	**113**	**140**	**140**	**114**
Not considered / newly built noise mitigation measures	10	12	12	10
Revised dataset after removal of not considered noise mitigation measures	**103**	**128**	**128**	**104**
Strong building influences (winter gardens, loggias, side panels…)	4	5	5	4
Revised dataset after additionally removing situations with building influences	**99**	**123**	**123**	**100**

In a second step the propagation conditions per measurement location were checked by comparing the modelled situation with pictures taken during the interviews. This first revision revealed that at 10 - 12 of the remaining measurement sites, sound propagation was shielded by noise barriers or in one case by a road cover, which had not been present in the original modelling. This led to a second, revised dataset with 103 - 128 measurements. In a third step, the measurement sites were checked for strong building influences on the sound propagation path such as side panels, winter gardens and loggias, which again were not represented in the modelling. Therefore, during this second revision step these measurements were removed and the analysis was redone with the remaining 99 to 123 measurements.

RESULTS

Figure 1 depicts the range of measured versus calculated noise levels for the different time periods. In the graphs grey triangles represent measurements which had been removed in the revision process due to not modelled noise barriers and/or strong influences at the receiver site.

As can be seen from Figure 1 the removed datasets show a strong overestimation of calculations compared to measurements. After revision the agreement is much better, however a slight tendency to underestimate the noise exposure at low levels and a slight overestimation at higher levels seems to remain.

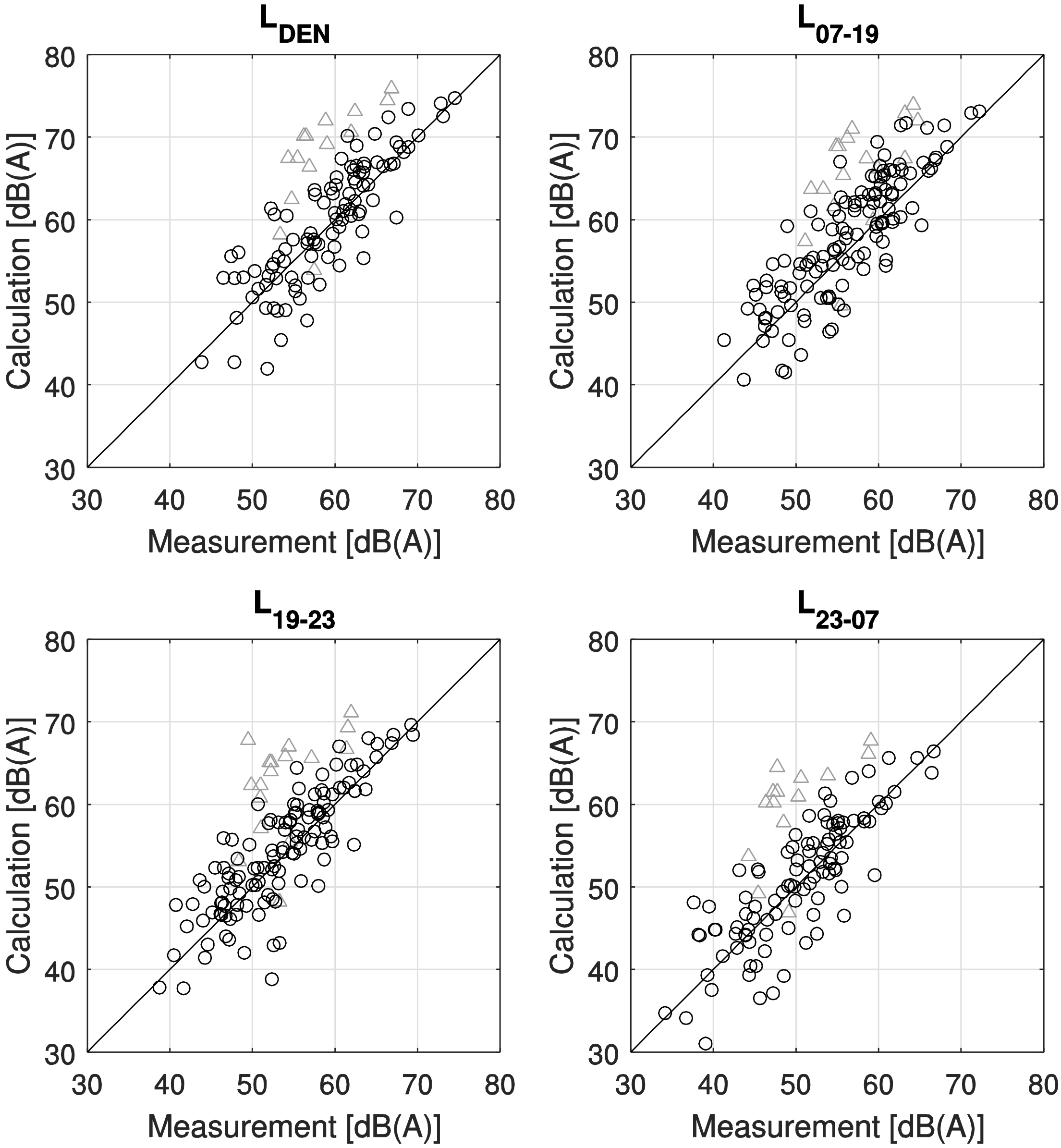

Figure 1: Scatterplots showing measured vs. calculated noise levels for different time periods. The grey triangles represent the removed measurements due to not modelled shielding (noise barriers and/or building interferences), while the black circles form the revised dataset.

Figure 2 shows the resulting differences in level between calculation and measurement as boxplots, on the left for the original dataset and on the right for the revised dataset. Table 2 tabulates the corresponding statistical figures.

The comparison reveals a substantial systematic overestimation of the calculated L_{DEN} in the original dataset of 1.5 dB(A), however only a small average overestimation in the revised dataset of 0.4 dB(A). Without the exclusion of the 4-5 measurement sites with strong building interferences such as side panels and loggias the mean of the deviation amounts to 0.7 dB(A) regarding L_{DEN}. Hence the overestimation in the original dataset is primarily caused by those 10-12 cases with not considered noise mitigation measures in the model and secondary by those 4-5 measurement sites with strong building interferences at the receiver site. After the exclusion of these measurements not only the average difference is substantially reduced but also the corresponding standard deviation.

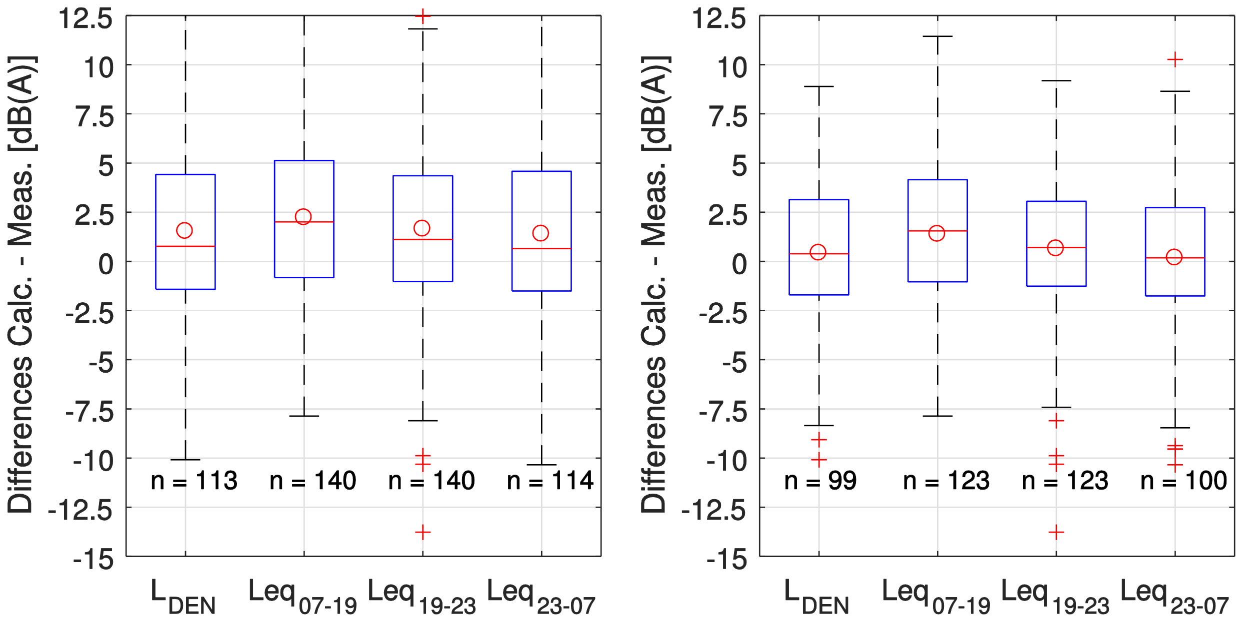

Figure 2: Differences between simulation and measurements in dB(A) displayed as boxplots (Red line: median, Box: 25 and 75% quartile, whiskers: 1.5 IQR) for different noise exposure levels. The red circles in the boxplots indicate the arithmetic mean of the differences. On the left side results are shown for the original dataset, on the right side for the revised dataset.

Table 2: Resulting statistical figures. On the left side results are shown for the original dataset, on the right side for the revised dataset.

	L_{DEN}	$L_{07\text{-}19}$	$L_{19\text{-}23}$	$L_{23\text{-}07}$
Mean [dB(A)]	1.5	2.2	1.6	1.4
StDev [dB(A)]	5.0	4.8	4.9	5.4
median [dB(A)]	0.8	2.0	1.1	0.6
q_{75} [dB(A)]	4.4	5.1	4.3	4.6
q_{25} [dB(A)]	-1.4	-0.8	-1.0	-1.5
n	113	140	140	114

L_{DEN}	$L_{07\text{-}19}$	$L_{19\text{-}23}$	$L_{23\text{-}07}$
0.4	1.4	0.6	0.2
4.0	4.1	3.9	4.3
0.4	1.6	0.7	0.2
3.1	4.2	3.0	2.7
-1.7	-1.0	-1.3	-1.8
99	123	123	100

The remaining overestimation in the exposure modelling is much more pronounced during the day. We suggested that this overestimation of levels during daytime might be due to reduced average travelling speeds during the day, as a consequence of dense traffic. To investigate this hypothesis, the dataset shall be separated into two groups. As the effect depends on a combination of impact factors such as daily traffic volume, street width, the number of lanes or speed limit a differentiation is complex. Therefore we simply assumed that such situations occur more often in urban situations. Thus a separation of the dataset into rural and urban locations was done, based on census data from the year 2015 from the Federal Statistical Office [15]. With the number of inhabitants of a municipality each measurement site was categorized to either rural or urban. For the classification a freely chosen threshold of 17 500 inhabitants was used, resulting in two datasets of comparable size.

Using this classification the revised dataset was reanalyzed as shown in Figure 3. The classified measurements reveal that the general trend of overestimating the measurements during the day time applies for both, rural and urban locations, however it is more pronounced at urban measurement locations. In general it is noticeable that the differences between simulation and measurement scatter more in urban than in rural areas. It can be assumed that both, propagation geometries and traffic situations (crossings, unsteady traffic flow, varying density of traffic) are more complex in urban situations and therefore cause a greater modelling uncertainty.

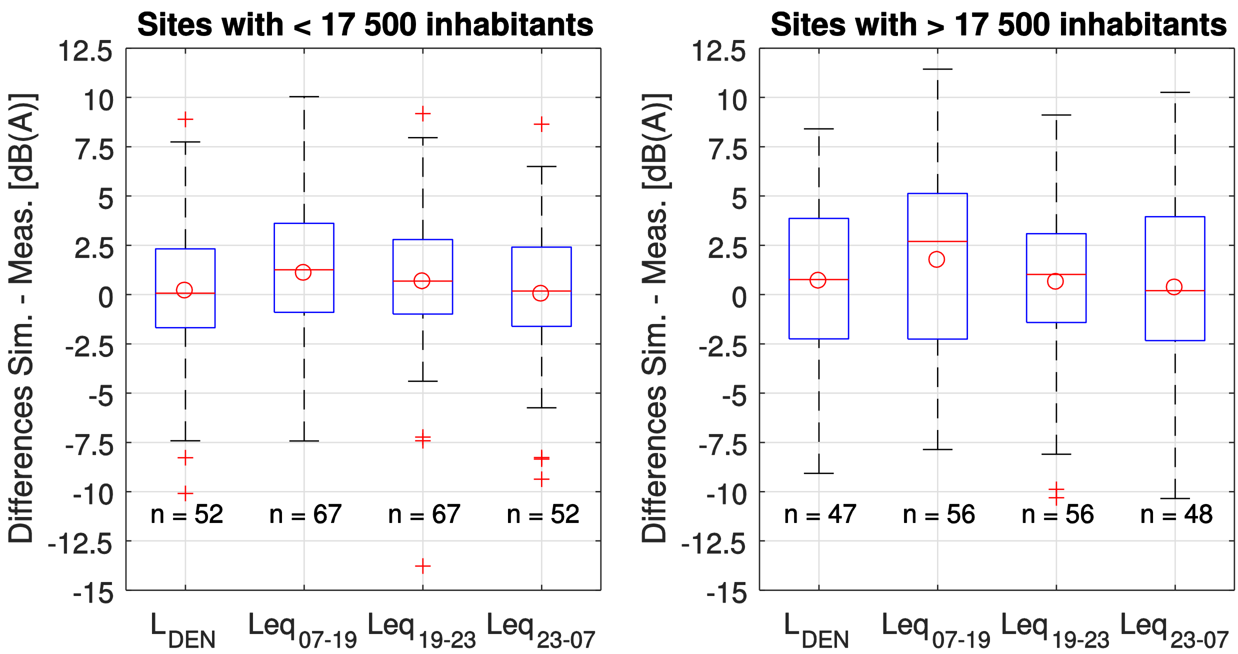

Figure 3: Differences between simulation and measurements in dB(A) displayed as boxplots boxplots (Red line: median, Box: 25 and 75% quartile, whiskers: 1.5 IQR) for different noise exposure levels. The red circles in the boxplots indicate the arithmetic mean of the differences. On the left side results are shown for rural sites, on the right side for urban sites.

In Table 3 the statistical key figures for the comparison between the simulated and measured noise levels categorized in more rural and urban measurement sites are shown.

Table 3: Resulting statistical figures. On the left side results are shown for the more rural measuring sites with less than 17 500 inhabitants, on the right side for more urban sites with more than 17 500 inhabitants

	L_{DEN}	L_{07-19}	L_{19-23}	L_{23-07}
Mean [dB(A)]	0.2	1.1	0.7	0.0
StDev [dB(A)]	3.7	3.6	3.8	3.8
median [dB(A)]	0.1	1.3	0.7	0.2
q_{75} [dB(A)]	2.3	3.6	2.8	2.4
q_{25} [dB(A)]	-1.7	-0.9	-1.0	-1.6
n	52	67	67	52

L_{DEN}	L_{07-19}	L_{19-23}	L_{23-07}
0.7	1.7	0.6	0.3
4.4	4.6	4.1	4.8
0.8	2.7	1.0	0.2
3.9	5.1	3.1	4.0
-2.2	-2.3	-1.4	-2.3
47	56	56	48

DISCUSSION

The comparison between modelled and measured noise exposure levels of the total dataset revealed a difference of 1.5 dB(A) regarding L_{DEN}. However, if the revised dataset with the exclusion of 14 – 17 locations is compared, the difference amounts to 0.4 dB(A), only. The exclusion of these locations has also a considerable effect on the scattering of the differences by reducing the standard deviation by about 1 dB(A).

With 10 - 12 locations a considerable percentage of situations had to be excluded during the first revision step. These locations were removed, because of mitigation measures that had not been present in the input data. This raises questions about the quality of the input data. It has to be kept in mind though, that the modeling was done for the year 2011, with input data from previous years. For example the noise barrier input data originate from 2010. Switzerland's Noise Abatement Ordinance (NAO) determines deadlines for noise mitigation measures for highways by 2015 and for main and other roads by 2018 [11]. Therefore numerous noise mitigation projects have been implemented in the past years at highly exposed locations, which explain why in many cases the measured situation in 2016 does not correspond to the situation of 2011 anymore.
In other 4 - 5 cases (depending on the timeframe) elements of the façade such as side panels, winter gardens or loggias caused an additional shielding of sound propagation. These measurement situations have been removed in a second revision step. In the input data buildings are generally only represented as cubes with no further details. In addition the sound propagation models are not designed to account for such effects. Therefore such structures cannot be taken into account in the modelling. Hence it can be concluded that the revised dataset allows estimating the accuracy of the acoustic model while the corrected dataset adds additional uncertainty for weaknesses of the input data.

Taking the measurement uncertainty into account it can be concluded that the exposure modelling within the SiRENE project does not exhibit a substantial systematic over- or underestimation. The range of uncertainty determined in the validation study is in full accordance with the uncertainty of the exposure modelling as previously stated for the SiRENE project [1].

However also for the revised dataset a slight general overestimation is remaining and a systematic trend towards higher calculated level during the day is visible. A possible explanation for this finding is likely to be found in the emission modelling of road traffic noise. Key factors for road noise generation are the driving speed as well as the amount and composition of traffic. It can often be noticed that in dense traffic the actually driven velocities are lower than the signaled speed limits. Dense traffic is much more probable for urban situations during daytime than for rural areas or nighttime. As the modelling was done with time-dependent traffic volumes, but with time-independent speed only, it is hypothesized that lower than assumed driving velocities are the primary reason for the general trend to overestimate the resulting sound exposure.

Another reason for the shown day-night behavior might be the temperature dependency of the rolling noise generation with gradients from -0.03 to -0.09 dB/°C depending on driving speed as well as pavement and tire type [16, 17]. However in the sonROAD emission model no temperature dependency is accounted for. Therefore the systematically higher temperatures during daytime are also likely to cause an overestimation of the modelled noise levels in comparison to the night.

Based on the current results the following recommendations can be made for future studies:

a) The remaining deviations and scattering are likely to be reduced by improved traffic flow models, which include locally varying travelling speeds for different vehicle classes, as functions of traffic density and under consideration of breaking and acceleration zones. In combination with more sophisticated emission models that account for temperature influences, the road emission modelling can be improved.

b) Great attention has to be given to the input data. Geo-referenced data has to exhibit a high positioning accuracy and must be fully up-to-date. In addition information about pavement properties is crucial for modeling road emissions and very difficult to retrieve in a satisfactory quantity and quality.

c) With improved input data also a higher level of sophistication in the propagation modeling is recommended, as especially in urbanized areas a detailed representation of reflections will become more important.

d) One general weakness of both, input data and sound propagation modelling, is that influences of the receiving building itself are fully ignored. Calculations generally only yield free field levels and do not account for the specific situation at the receiver point. However it is current practice for constructions in areas with high noise exposure to optimize balconies, loggias and other constructive elements in a way, that noise is shielded as good as possible. The resulting reduction however is not represented in current exposure modelling. It is therefore recommended to aim for more detailed building data and more sophisticated sound propagation models, which are able to account for complex barrier effects and multiple reflection paths.

With this validation study it was shown that the emission modelling within SiRENE resulted in no systematic over- or underestimation of noise levels. However the scattering between the measured and calculated sound exposure is considerable due to modelling, measuring and input data uncertainties. Thus, the goal for future studies is to reduce the scattering and consequently derive even more accurate noise emission predictions.

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