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Conversion between noise exposure indicators Leq24h, LDay, LEvening, LNight, Ldn and Lden: Principles and practical guidance

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Abstract:

This article presents empirically derived conversion rules between the environmental noise exposure metrics Leq24h, LDay, LEvening, LNight, Ldn, and Lden for the noise sources road, rail and air traffic. It caters to researchers that need to estimate the value of one (unknown) noise metric from the value of another (known) metric, e.g. in the scope of epidemiological meta-analyses or systematic reviews, when results from different studies are pooled and need to be related to one common exposure metric. Conversion terms are derived using two empirical methods: a) based on analyzing the diurnal variation of traffic, and b) by analyzing differences between calculated noise exposure metrics. For a) we collected and analyzed diurnal traffic share data from European and US airports as well as data on the diurnal variation of traffic from roads in several European countries and from railway lines in Switzerland which were derived from counting stations and official records. For b) we calculated differences between noise metrics in over 50'000 stratified randomly sampled dwellings in Switzerland. As a result of this exercise, conversion terms, including uncertainty estimates, are systematically tabulated for all variants of the target metrics. Guidance as to the practical applicability of the proposed conversions in different contexts is provided, and limitations of their use are discussed.

Keywords:

Noise exposure, noise indicator, noise metric, conversion

Running title:

Conversion between noise exposure indicators

1 Introduction

Scientifically substantiated noise protection policies are usually based on systematic reviews or meta-analyses of noise-induced health effects, considering the evidence from many original studies. For combining and evaluating the evidence of the effect of noise exposure on a certain health outcome, the quantification of the noise exposure calls for a common unit, also called noise metric or noise indicator, based on which the results from different studies can be compared. Today, there are more than a handful of different noise metrics in use. The most common types are yearly long-term average A-weighted equivalent sound pressure levels that integrate the time-varying noise level of a particular source over a specific period of the day (e.g. 24 hours, or the day or the night), or compound metrics that include a penalization of the evening and/or nighttime (e.g. L_{dn} or L_{den}) to account for the elevated noise sensitivity in these time periods.

Country-specific legislation often determines the availability of particular noise metrics to authors of original studies, with the consequence that a range of different (incompatible) metrics are being used in the pertinent literature. This is unfavorable for any type of meta study where the researcher must decide on a common metric to relate noise effects to. If the noise exposure data in the original studies have not been reported in the desired metric, one needs to apply some rule of thumb to convert the value of the known metric to the value in the metric of interest. Strikingly, the peer-reviewed literature on conversions between the different metrics is scarce if not inexistent.

Conversion rules published so far can be found in (appendices of) policy documents (e.g. Abbott and Nelson, 2002; European Commission, 2002b; European Environmental Agency, 2010) or as part of conference proceedings (e.g. Naish et al., 2011; van den Berg, 2008) or technical reports, especially regarding aircraft noise (e.g. Deutsches Zentrum für Luft- und Raumfahrt, 1999; Umweltbundesamt, 1984). The more policy-oriented publications often lack a detailed description of the derivation of the proposed conversion rules as well as their range of application, their limitations and their corresponding uncertainties. The present study thus aimed at estimating generically applicable conversion rules, including their standard uncertainty, for the traffic noise sources road, rail, and air, for the L_{eq24h}, L_{Day}, L_{Evening}, L_{Night}, L_{dn}, and L_{den} metric, and provides some guidance regarding their practical application. The conversion rules consist of additive conversion terms that are specific for the transportation noise source considered. The conversion terms are systematically tabulated for easy lookup.

2 Theoretical background

While for an individual receiver point the noise level as expressed in one particular metric cannot be predicted by the noise level in another metric in a deterministic fashion, on average, energy-based noise metrics are often highly correlated, and simple transformations from one metric to another are – within limits – possible. Provided the composition and routing of the noise-producing vehicle fleet (cars, trains, airplanes etc.) as well as sound propagation conditions are relatively constant across a day at a given receiver point, deriving conversions between two metrics is relatively straightforward. In such cases, hourly traffic shares can directly be interpreted as fractions of acoustic energy, which can be summed up and related to one another as shown in Figure 1. It indicates the level difference (in dB) between a few select metrics based on the proportion of night-time traffic within the 24-hour

period. The level difference curves are based on an idealized constant vehicle mix, vehicle routing and stable atmospheric conditions across all hours of a day.

(Figure 1 here)

While the level difference curves shown in Figure 1 are the result of a theoretical approximation, in reality, the temporal distribution, the routing and the composition of the vehicle fleet always varies to some extent. As regards the metrics that are in the focus of this paper, the differences between them are certainly determined by the diurnal variation of traffic volumes, but also by diurnal variations in the vehicle fleet (composition of vehicle / train / aircraft types). Time-varying routing particularly plays a role for aircraft noise. In the case of road traffic also diurnal variations of the speed distribution can be of relevance as the speed influences sound power and exposure duration. Diurnal variation of traffic volume strongly depends on the source (roads, railways, aircraft) and is driven by the rhythm of commercial and leisure activities that generate mobility, particularly in the case of road traffic. The distribution of traffic (operations) across a day, preferably in subsequent 1-hour time slices, is therefore one of the primary sources to estimate generic conversion rules between different noise metrics. The respective information can e.g. be obtained from road traffic counting stations. Such provide the percentage of the *annual average daily traffic* (AADT) in each hour, reflecting the temporal distribution of the usage of roads. To visualize this exemplarily, Figure 2 displays the hourly distribution of the AADT in Switzerland in 2011, measured at 307 official counting stations across the country, for two road categories with different average speeds (main and connection roads vs. highways) and two vehicle categories (heavy vehicles vs. light vehicles). It is important to note that the AADT (per hour) represents the yearly average (per hour), and thus also averages out differences in the usage of roads between workdays and weekend days or in different seasons in a specific hour of the day.

(Figure 2 here)

As regards vehicle composition, a specific vehicle type at one exposure point may not exactly follow the average diurnal distribution of all vehicle types together. As different vehicle types have different acoustical emission levels (e.g. cars vs. trucks), simply counting the number of vehicles (of any type) could result in a biased estimate of the relationship between two metrics. Furthermore, there could be night curfews in place (for certain roads and/or vehicle types) that affect the exposure at one receiver point during nighttime, but not at another. For deriving generic ("one fits all") conversion terms applicable to a wide range of situations, the relevant question is how strongly these bespoke factors play a role. While deriving conversions based on diurnal traffic shares seems feasible in the case of road traffic noise, things get more challenging for railway noise and are even more complex for aircraft noise.

In the next section, we describe how to overcome some of the difficulties stated above and introduce two approaches to conversion that were both used in the present study.

Results for all conversion terms between metrics along with their uncertainties are given concisely in tabulated form in Section 4. Uncertainty in this context is defined in analogy to the Guide to the expression of uncertainty in measurement (GUM) (ISO/IEC, 2008) as a "parameter, associated with

the result of a measurement [*or calculation*], that characterizes the dispersion of the values that could reasonably be attributed to the measurand [*or calculation result*]⁷. It corresponds to the standard deviation of a normal distribution, i.e. to the 68% confidence interval.

3 Methods

There are basically two methods to derive a conversion term between two energy-based noise metrics: The first is based on information about the diurnal variation of traffic of a given source, e.g. from automatic traffic counting stations on roads and from other pertinent operational information in the case of railway and air traffic, hereafter referred to as "traffic share method". The primary goal of this approach is to estimate the average proportion of acoustic energy of the respective source received at an average exposure point in each hour across the 24-hour day. Once these 24 figures are determined, the translation of the diurnal variation of traffic to a difference between two metrics can be carried out by building the logarithm of the fraction of the time-averaged acoustic energy of the two metrics, which both can be calculated from the 24 previously determined figures, including penalty terms were necessary.

The second method is based on calculated (modelled) noise exposure and relies on empirically determining differences between noise metrics in a representative sample of receiver points where more than one metric has been calculated, hereafter referred to as "noise-exposure method".

In this paper, we will use one or the other or both of these methods for each source, depending on the availability of input data and its adequacy for the purpose at stake.

3.1 Definition of noise metrics

As there are no universally accepted definitions of the time periods "day", "evening", and "night", we provide in this paper the conversion terms between all the most commonly used variants of noise metrics, which shall be defined as follows:

$$L_{Aeq24h} = 10 \cdot \lg \left(\frac{1}{24} \cdot \sum_{H=0}^{23} 10^{0.1 L_{Aeq,H}} \right) \quad (1)$$

$$L_{Day^a} = 10 \cdot \lg \left(\frac{1}{16} \cdot \sum_{H=6}^{21} 10^{0.1 L_{Aeq,H}} \right), \quad L_{Day^b} = 10 \cdot \lg \left(\frac{1}{16} \cdot \sum_{H=7}^{22} 10^{0.1 L_{Aeq,H}} \right) \quad (2)$$

$$L_{Day^c} = 10 \cdot \lg \left(\frac{1}{12} \cdot \sum_{H=7}^{18} 10^{0.1 L_{Aeq,H}} \right) \quad (3)$$

$$L_{Night^a} = 10 \cdot \lg \left(\frac{1}{8} \cdot \sum_{H=22}^5 10^{0.1 L_{Aeq,H}} \right), \quad L_{Night^b} = 10 \cdot \lg \left(\frac{1}{8} \cdot \sum_{H=23}^6 10^{0.1 L_{Aeq,H}} \right) \quad (4)$$

$$L_{\text{Evening}^a} = 10 \cdot \lg \left(\frac{1}{4} \cdot \sum_{H=18}^{21} 10^{0.1 L_{\text{Aeq},H}} \right), \quad L_{\text{Evening}^b} = 10 \cdot \lg \left(\frac{1}{4} \cdot \sum_{H=19}^{22} 10^{0.1 L_{\text{Aeq},H}} \right) \quad (5)$$

$$L_{\text{dn}^a} = 10 \cdot \lg \left(\frac{1}{24} \cdot \left(\sum_{H=7}^{21} 10^{0.1(L_{\text{Aeq},H})} + \sum_{H=22}^6 10^{0.1(L_{\text{Aeq},H} + K_n)} \right) \right) \quad (6a)$$

$$L_{\text{dn}^b} = 10 \cdot \lg \left(\frac{1}{24} \cdot \left(\sum_{H=7}^{22} 10^{0.1(L_{\text{Aeq},H})} + \sum_{H=23}^6 10^{0.1(L_{\text{Aeq},H} + K_n)} \right) \right) \quad (6b)$$

$$L_{\text{dn}^c} = 10 \cdot \lg \left(\frac{1}{24} \cdot \left(\sum_{H=6}^{21} 10^{0.1(L_{\text{Aeq},H})} + \sum_{H=22}^5 10^{0.1(L_{\text{Aeq},H} + K_n)} \right) \right) \quad (6c)$$

$$L_{\text{den}^a} = 10 \cdot \lg \left(\frac{1}{24} \cdot \left(\sum_{H=6}^{17} 10^{0.1(L_{\text{Aeq},H})} + \sum_{H=18}^{21} 10^{0.1(L_{\text{Aeq},H} + K_e)} + \sum_{H=22}^5 10^{0.1(L_{\text{Aeq},H} + K_n)} \right) \right) \quad (7a)$$

$$L_{\text{den}^b} = 10 \cdot \lg \left(\frac{1}{24} \cdot \left(\sum_{H=7}^{18} 10^{0.1(L_{\text{Aeq},H})} + \sum_{H=19}^{22} 10^{0.1(L_{\text{Aeq},H} + K_e)} + \sum_{H=23}^6 10^{0.1(L_{\text{Aeq},H} + K_n)} \right) \right) \quad (7b)$$

with:

H Index for the hour of the day [Example: H=0 is the hour from 00:00 to 00:59:59; H=19 is hour 19:00 to 19:59:59]

$L_{\text{Aeq},H}$ A-weighted yearly averaged long term L_{eq} within hour H

Penalties: $K_e = 5 \text{ dB}$, $K_n = 10 \text{ dB}$

Note: For noise impact assessments and noise mapping, L_{dn}^a (Equation 6a) is commonly used in the USA (where the L_{dn} is called DNL) (Environmental Protection Agency (EPA), 1974) and L_{den}^b (Equation 7b) in the European Union (European Commission, 2002a).

3.2 Conversion estimation based on traffic volume data (traffic share method)

For two of the three noise sources considered in the present exercise (road traffic and aircraft noise) we obtained data of diurnal distributions of traffic volume as a starting point for deriving conversion terms. We used comprehensive yearly average road traffic flow data from Switzerland, Germany, the Netherlands, Belgium, the UK, and France to estimate the diurnal distribution of the exposure of that source, and air traffic data from European and US airports for aircraft noise, as described in the following.

3.2.1 Road traffic noise

As a first step, we collected the AADT data of the year 2011 from all 307 road traffic counting stations operated by the Swiss Automatic Road Traffic Counts (SARTC) network and the corresponding AADT data from the German Federal Highway Research Institute (BAST), covering all 1418 official traffic counting stations on highways ("Bundesautobahnen") and federal roads ("Bundesstraßen") in Germany (Bundesanstalt für Straßenwesen, 2015). Countrywise, for each hour of the day at each counting station, we estimated the fraction of the daily emitted acoustic energy by considering the diurnal distribution of traffic counts, separately for light and heavy vehicles. To account not just for the hourly variation of the number of vehicle pass-by events, but also for their acoustic energy, the proportion of heavy vehicles was weighted according to their estimated excess of sound power per pass-by compared to that of a passenger car or motorbike (here considered light vehicles) depending on the estimated average speed per road category. We calculated the corresponding weights based on the A-weighted sound pressure emission spectra of the vehicle categories defined in CNOSSOS (European Commission, 2015): For main and connection roads with an estimated average speed of all vehicle categories of 50 km/h, heavy vehicles were weighted with +8.3 dB, corresponding to a power factor of 6.76. On highways, assuming 80 km/h average speed of an average heavy vehicle, the additional sound energy of heavy vehicles is just +1.7 dB, corresponding to a power factor of 1.48, compared to light vehicles with an assumed average speed of 120 km/h. Note that these weightings account for systematic differences in sound power and pass-by duration. Differences in sound propagation, emerging e.g. from different source heights and spectral content and resulting in different propagation attenuations, cannot be accounted for here, because the specific exposure situation for which the conversions will be applied is unknown. For each counting station, we first calculated the energy fractions for each hour of the day (F_H) and then calculated level differences (expressed in dB) between any two of the metrics introduced above by building the logarithm of the fraction of the time-averaged acoustic energy of the two metrics, including weighting of the energy in the time periods used in the composite metrics L_{den} and L_{dn} , using the power factors $10^{0.5} = 3.16$ (evening hours) and $10^1 = 10$ (night-time hours) where necessary. In the following equation, this basic procedure is exemplified for the conversion from L_{den}^b (cp. Equation 7a) to L_{Night}^a (cp. Equation 4).

$$L_{den}^b - L_{Night}^a = 10 \cdot \lg \left(\frac{\frac{1}{24} \cdot \left(\left(\sum_{H=7}^{18} F_H \right) + \left(3.16 \sum_{H=19}^{22} F_H \right) + \left(10 \sum_{H=23}^6 F_H \right) \right)}{\frac{1}{8} \cdot \left(\sum_{H=22}^5 F_H \right)} \right) \quad (8)$$

with:

F_H Fraction of the acoustic energy in hour H (F_H), Note that $F_0 + F_1 + F_2 \dots + F_{23} = 1$

In the last step we calculated conversion terms as the mean of the level differences across all counting stations for each pair of metrics to be compared. Similarly, we calculated the standard uncertainty of these differences as the standard deviation of the differences across all counting stations.

We furthermore obtained aggregated AADT data in an hourly resolution from the Netherlands (year 2013), Belgium/Flanders (2014), the whole UK (2011) (Department for Transport, 2015), and the populous Île-de-France region in France (2011) (Direction des routes Île-de-France (<http://www.enroute.ile-de-france.developpement-durable.gouv.fr/les-comptages-a174.html>), 2011). Also for these countries we estimated the average fraction of the acoustic energy in hour H (F_H). In case the hourly proportion of heavy vehicles was not known, we assumed the same average values as in Switzerland. Heavy vehicles were then weighted with an estimated average power factor of 5 (+6.99 dB compared to light vehicles). The inclusion of country-specific data sets broadens the empirical basis for estimating conversion terms and allows comparing the diurnal road traffic noise variation between countries. The resulting patterns of the diurnal road traffic noise distribution are tabulated in Table 1 and plotted in Figure 3.

Table 1: Average proportion of the total acoustic energy of road traffic noise produced in each hour H (F_H), by country. The values were derived by weighting the respective average proportion of vehicle pass-by events by light or heavy vehicles.

F_H	H=0	H=1	H=2	H=3	H=4	H=5	H=6	H=7	H=8	H=9	H=10	H=11
Switzerland	0.008	0.005	0.004	0.004	0.006	0.019	0.046	0.061	0.058	0.058	0.064	0.066
Germany	0.009	0.007	0.007	0.008	0.012	0.025	0.045	0.058	0.057	0.058	0.060	0.062
Netherlands	0.010	0.006	0.005	0.005	0.008	0.021	0.048	0.062	0.062	0.058	0.057	0.059
Belgium (Flanders)	0.010	0.006	0.005	0.006	0.010	0.023	0.039	0.054	0.058	0.056	0.058	0.059
France (Île-de-France)	0.014	0.010	0.009	0.009	0.013	0.025	0.045	0.054	0.057	0.057	0.058	0.060
United Kingdom	0.007	0.005	0.005	0.005	0.008	0.019	0.037	0.063	0.073	0.066	0.067	0.068
F_H	H=12	H=13	H=14	H=15	H=16	H=17	H=18	H=19	H=20	H=21	H=22	H=23
Switzerland	0.060	0.067	0.069	0.071	0.077	0.077	0.061	0.042	0.028	0.021	0.017	0.012
Germany	0.063	0.067	0.069	0.070	0.073	0.068	0.056	0.041	0.030	0.022	0.018	0.013
Netherlands	0.061	0.064	0.065	0.069	0.075	0.073	0.057	0.041	0.032	0.026	0.022	0.016
Belgium (Flanders)	0.062	0.065	0.066	0.069	0.076	0.076	0.064	0.046	0.033	0.026	0.020	0.014
France (Île-de-France)	0.058	0.057	0.060	0.061	0.064	0.063	0.060	0.054	0.041	0.028	0.022	0.019
United Kingdom	0.065	0.067	0.068	0.070	0.073	0.069	0.054	0.039	0.028	0.020	0.014	0.010

(Figure 3 here)

In the results section further below, Table 6a shows conversion terms as the average of the country-specific datasets, yielding a conversion matrix representative for Western Europe. The combined standard uncertainty of the conversion terms in Table 6a is reflected in Table 6b and was estimated by considering three uncertainty components: (1) the variability of the conversion terms between countries, (2) the variability of the conversion terms between traffic counting stations, and (3) the variability of the conversion terms as derived by the noise-exposure method (cp. Section 3.3 below). For the uncertainty component "variability between traffic counting stations", we used – in a conservative approach – the standard deviations from Switzerland as they were larger than those

we found for Germany. The three uncertainty components were combined according to the Guide to the expression of uncertainty in measurement (GUM) (ISO/IEC, 2008). We did not include the variability of the difference between the traffic share and the noise-exposure method in Switzerland as a fourth uncertainty component because the differences in the conversion terms between the metrics as determined by the two methods were found to be small (< 0.5 dB on average).

Note that as the conversion terms in Table 6a rather reflect the (Western) European *average*, they may not perfectly correspond with the situation in a particular country, even if it is also located in Western Europe.

3.2.2 Railway noise

While for road traffic noise the number of vehicles (per hour) is a feasible proxy variable for the sound emission of the corresponding road section (or traffic counting station to be more precise), this is much less the case for railway noise. On one hand the sound emission between trains varies much more, and on the other, there is a strong interaction between the track properties, primarily the rail roughness, and the rolling stock properties, primarily the type of braking system. As a consequence neither the total sound emission per train nor the relative sound emission between wagons of different categories can be assumed to be constant along the railway network. We therefore decided to not directly use operational railway traffic data for the calculation of conversion terms between metrics for railway noise, but to rather rely on the noise-exposure method as described in Section 3.3.

3.2.3 Aircraft noise

Problem overview

It was an a priori assumption that varying operational conditions and complexities at different airports would lead to higher uncertainties of conversion terms, compared to road or railway traffic. Besides diurnal variation of aircraft movements and fleet composition, also the number, orientation, and usage of runways and the air route system of an airport play an important role, especially if operating directions tend to often change during day, as is the case for example for London Heathrow (LHR), a large airport, or Zurich (ZRH), a medium-sized airport. Also, some airports have night curfews in force. Thus, deriving conversion terms between day and night exposure metrics from an airport with a night curfew and applying it to an airport without any curfew will inevitably lead to error-prone conversions.

The relationship between LN_{Night} and LN_{Day} at grid points in a rectangular grid with a mesh size of $250 \text{ m} \times 250 \text{ m}$ around two different Swiss airports (Zurich (ZRH) and Geneva (GVA)) are shown as scatterplots in Figure 4. They were produced with the idea in mind that if a day exposure metric is contrasted with a night exposure metric, with mutually exclusive time periods (here, 22 to 6 hours vs. 6 to 22 hours), one can expect the largest possible scattering of points for a single airport. This should nicely reveal the potential amount of uncertainty one is confronted with when deriving conversion terms from and for a single airport. The exposure data shown in Figure 4 were obtained based on detailed traffic and sound source data with the aircraft noise calculation model FLULA2, Version 004 (Empa, 2010; Pietrzko and Hofmann, 1988) using complete data sets of radar-tracked

individual flight trajectories of the year 2011 (Schäffer et al., 2011). As the plots reveal, the scattering of data points and the corresponding prediction interval is larger in case of ZRH compared to GVA, which also exhibits a slightly steeper slope of the regression line between LNight and LDay. These differences are the result of a more complex air route system and three runways in ZRH as compared to one runway and a rather simple operation of in- and outbound air routes in GVA.

(Figure 4 here)

Normally, the availability of exposure data in a complete mesh grid around an airport is highly limited as such data are not usually published or otherwise easily accessible. While it is possible to derive a spatially precise average conversion rule for one airport (like e.g. GVA) based on grid data from that airport, this method precludes "representativity" for a larger range of airports (i.e. for all major European airports). Fortunately, data on the diurnal variation of air traffic movements (in an hourly resolution) are often published by airports as part of their environmental reporting. To make use of that kind of information (and hence the "traffic share method") was found to be a more promising avenue to establish conversion terms in the present case (although the "noise-exposure method" would be clearly preferred from a technical point of view). We therefore collected data on the annual diurnal distribution of air traffic movements from European and US airports for estimating average conversion terms, as described in the following.

Calculation

As with road traffic (cp. Section 3.2.1), the major goal in the estimation of generic conversion parameters for aircraft noise is to calculate the average proportion of the total acoustic energy produced by aircraft (or, more to the point, by *airports*) in each hour H across a day in a sample of airports that can be regarded representative for today's air traffic. To this end, we obtained data on the diurnal variation of the number of movements from 48 large ($> 50\,000$ annual movements) civil airports, namely, 28 European and 20 US airports, with data on diurnal variation for 1 to 29 (mostly recent) years per airport, resulting in a total of 147 individual yearly diurnal traffic distributions. The collection covers a wide range of airport sizes, with average yearly movements ranging from $\sim 62\,000$ to $\sim 487\,000$ in Europe and from $\sim 313\,000$ to $\sim 880\,000$ in the US. The yearly night-time air traffic (23:00–07:00 h) of the sampled airports accounted for 0–46% (Europe) and 5–14 % (US) of the total yearly air traffic (averages over the available years per airport). Figure 5 (left) shows for each hour of the day the share of the annual average daily air traffic (AADT), as averaged per airport over the available individual years.

The present sample of airports could not be created on the basis of a pre-defined representativity for geographical regions and/or years, as we were fully depending on the cooperation of airport authorities to share their traffic data with us. However, a comparison of the resulting averaged relative diurnal distributions of the sampled US and European airports with the respective complete data for EU-EFTA airports (EUROCONTROL, 2017) revealed neither large nor systematic differences between the diurnal profiles (cp. Figure 5 right). Therefore, our sample can be considered as representative for European as well as for US airports.

(Figure 5 here)

To estimate the conversion terms between noise metrics for aircraft noise (Table 8a), we applied the same procedure as described above for road traffic noise. First, we estimated the proportion of the acoustic energy emitted by air traffic around individual airports in individual years in each hour across the 24 hour day, based on the 147 individual diurnal traffic distributions. The resulting values per year and airport were then averaged per airport, and then across all airports. The combined standard uncertainty of aircraft noise conversion terms (Table 8b) was estimated by considering three uncertainty components: (1) the standard uncertainty of the diurnal traffic share of the 48 selected airports, (2) the standard uncertainty derived by the noise-exposure method in the three Swiss airports Basel (BSL), GVA and ZRH, and (3) the standard uncertainty of the difference between the results obtained with the noise-exposure and the traffic share method, determined for GVA and ZRH in the year 2011. The uncertainty due to variation in the conversion terms of a specific airport between years is negligible as it was found to be small compared to the above three uncertainty components. The uncertainty components were again combined according to the GUM (ISO/IEC, 2008).

3.3 Conversion estimation based on calculated exposure data in a sample of receiver points (noise-exposure method)

The calculation of conversion parameters by the noise-exposure method, here carried out for road and railway traffic noise, was accomplished by determining the average difference between all considered exposure metrics in a representative sample of receiver points. As a primary sampling frame for this exercise, we used the country-wide calculation of the Swiss transportation noise database (sonBASE) which was specifically carried out for the SiRENE project (Short and long term effects of transportation noise exposure) described elsewhere (Röösli et al., 2017). SonBASE covers road traffic, railway and aircraft noise and has been constantly updated and refined since its initial launch in 2009 (Bundesamt für Umwelt, 2009). The current version contains the long term average exposure values for the reference year 2011 for the three noise sources road, rail and air in an hourly resolution for over 50 Mio. facade points assigned to roughly 6.9 Mio. dwelling units (e.g. apartments) and covers the full population of Swiss buildings. The detailed timely resolution allows to calculate all noise metrics defined in Equations (1) to (7b).

Within sonBASE, road traffic input data are created by traffic volume models that combine data from traffic census monitoring systems (cp. Fig. 2) with Swiss census data of the population and of business enterprises to generate traffic information also for the street sections not represented by counting stations. For railway noise, traffic data is derived from the combination of the route pricing system i-Prix and the infrastructure database PandA of the Swiss federal railways (SBB), which records the total number of trains and vehicles per category for each section of the Swiss railway network.

Sampling procedure

Instead of using all data from all dwelling units in the database we opted for a stratified sampling approach to create a reduced and more manageable set of records. We drew dwelling units randomly from sonBASE according to a factorial design that accounted for three sources (road, rail, air), two time periods ($L_{Aeq,16h,Day}$ and $L_{Aeq,08h,Night}$), ten 2.5 dB wide exposure categories in the range between <45 dB(A) and >65 dB(A) (for the day period) and between <35 dB(A) and >55 dB(A) (for the night period) and 3 "intermittency ratio" categories (see below) calculated as "low", "medium", or "high". In each factor combination (of in total 180), we drew a random sub-sample of 300 dwelling units, which is large enough a number to be representative for the respective factor combination. As some factor combinations were rarer than 300 cases in the whole country, we ended up with a sample of 52'030 dwelling units to work with. The facade points on these dwelling units reflect a stratified random sample of exposure situations across Switzerland, that fully account for propagation conditions, and encompass rural, suburban, and urban areas.

The primary reason for this stratified approach is that a conversion calculation based on the entire population of dwelling units (or a random sample thereof) would rather reflect the average conditions in Switzerland, but maybe less accurately do so elsewhere, as the frequency distribution of noise exposure levels at facade points can vary – maybe substantially – between countries. Just using the Swiss population of dwelling units would reflect primarily Swiss conditions. Secondly, low-level exposure modeling is usually less accurate and thus restricting the analyses to the midrange and higher noise exposure levels should increase the accuracy of all calculations, including those to assess conversion terms. Lastly, a non-stratified sample (or whole population) would underrepresent situations with e.g. very high average levels (because such are comparatively rare).

The metric intermittency ratio (IR) is one of the design factors in the stratified sample. It was developed within the SiRENE study and accounts for the "eventfulness" of an exposure situation (Brink et al., 2016; Wunderli et al., 2016). IR takes values between 0 and 100%. An IR >50% means that more than half of the sound dose is caused by "distinct" pass-by events (e.g. from individually distinguishable vehicles). In situations with only noise events that clearly emerge from background noise (e.g., a receiver point close to a railway track), IR yields values close to 100%, whereas for a distant motorway that rather continuously emits noise, IR is close to 0%. Thus, IR partly reflects the type of road and therefore also potentially different temporal diurnal usages of different road types. Using IR as a stratification criterion balances these different road types in the sample.

Once a dwelling unit was sampled, noise exposure of all sources at all of its façade points was assigned. However, in the following, we restricted the analysis to the loudest facade point for each source, as that point generally has the smallest calculation uncertainty. Finally, for each source, exposure values below 30 dB L_{Day}^a (cp. Equation 2) and below 20 dB L_{Night}^b (cp. Equation 4) were excluded from the sample. Figure 6 displays the sampled dwelling units as blue dots alongside with L_{den} noise contour maps for road and railway noise in the sample.

(Figure 6 here)

Determination of conversion terms

For the final analyses, conversion terms between all noise metrics were determined by calculating the averages of all differences between all metrics in N=51'741 dwelling units for road traffic noise, and in N=31'271 dwelling units for railway noise. Standard uncertainties were assessed as the standard deviations.

Conversion terms between metrics for Swiss road traffic noise were determined both by the "traffic share" and the "noise-exposure" method and compared to each other. As mentioned before, this comparison revealed only very small absolute differences (which were < 0.5 dB on average).

Conversion terms for railway noise as derived by the method described above, are given in Table 7a, the corresponding uncertainties are given in Table 7b.

4 Conversion result tables

In the following, conversion terms, including uncertainties, are tabulated separately for road traffic noise (traffic share method using European road traffic data), railway noise (noise-exposure method using Swiss railway noise exposure data), and aircraft noise (traffic share method using European and US air traffic data). They are suitable for the conversion of metrics that express the yearly long-term average level. To build the conversion equation, the desired metric should be identified in the first column ("Desired metric"), then the conversion term to be added or subtracted is indicated on the row of the desired metric, for different known metrics ("Known metric" columns). For example, using the 9th row of Table 6a (road traffic), $LNight^b$ can be estimated from $Lden^a$ by using the conversion rule $LNight^b = Lden^a - 8.0 \text{ dB}$.

4.1 Road traffic noise conversions

Table 6a: Average of estimated conversion terms between two different noise metrics (cp. Equations (1)-(7b)) for road traffic noise, derived from AADT data from the following countries and years: Switzerland 2011; Germany 2011, the Netherlands 2013, Belgium/Flanders 2014, the UK 2011, and France/Île-de-France 2011, in decibels [dB]

	↓ Known metric ↓												
↓ Desired ↓ metric	LDay ^a	LDay ^b	LDay ^c	LNight ^a	LNight ^b	LEvening ^a	LEvening ^b	LAeq24 ^h	Lden ^a	Lden ^b	Ldn ^a	Ldn ^b	Ldn ^c
LDay ^a =		+0.1	-0.5	+7.1	+6.0	+1.6	+2.9	+1.3	-2.0	-2.3	-2.1	-1.8	-1.3
LDay ^b =	-0.1		-0.6	+6.9	+5.9	+1.5	+2.8	+1.2	-2.1	-2.4	-2.2	-1.9	-1.4
LDay ^c =	+0.5	+0.6		+7.6	+6.5	+2.1	+3.4	+1.8	-1.5	-1.8	-1.6	-1.2	-0.8
LNight ^a =	-7.1	-6.9	-7.6		-1.1	-5.5	-4.2	-5.7	-9.1	-9.3	-9.2	-8.8	-8.3
LNight ^b =	-6.0	-5.9	-6.5	+1.1		-4.4	-3.1	-4.7	-8.0	-8.3	-8.1	-7.7	-7.3
LEvening ^a =	-1.6	-1.5	-2.1	+5.5	+4.4		+1.3	-0.3	-3.6	-3.9	-3.7	-3.4	-2.9
LEvening ^b =	-2.9	-2.8	-3.4	+4.2	+3.1	-1.3		-1.5	-4.9	-5.1	-5.0	-4.6	-4.1
LAeq24h =	-1.3	-1.2	-1.8	+5.7	+4.7	+0.3	+1.5		-3.3	-3.6	-3.4	-3.1	-2.6
Lden ^a =	+2.0	+2.1	+1.5	+9.1	+8.0	+3.6	+4.9	+3.3		-0.3	-0.1	+0.3	+0.7
Lden ^b =	+2.3	+2.4	+1.8	+9.3	+8.3	+3.9	+5.1	+3.6	+0.3		+0.2	+0.5	+1.0
Ldn ^a =	+2.1	+2.2	+1.6	+9.2	+8.1	+3.7	+5.0	+3.4	+0.1	-0.2		+0.3	+0.8
Ldn ^b =	+1.8	+1.9	+1.2	+8.8	+7.7	+3.4	+4.6	+3.1	-0.3	-0.5	-0.3		+0.5
Ldn ^c =	+1.3	+1.4	+0.8	+8.3	+7.3	+2.9	+4.1	+2.6	-0.7	-1.0	-0.8	-0.5	

Table 6b: Combined standard uncertainties of estimated conversion terms for road traffic noise (cp. Section 3.2.1), in decibels [dB]

	↓ Known metric ↓												
↓ Desired ↓ metric	LDay ^a	LDay ^b	LDay ^c	LNight ^a	LNight ^b	LEvening ^a	LEvening ^b	LAeq24 ^h	Lden ^a	Lden ^b	Ldn ^a	Ldn ^b	Ldn ^c
LDay ^a		0.1	0.2	1.9	1.7	1.0	1.3	0.1	0.8	0.8	0.8	0.8	0.8
LDay ^b	0.1		0.2	2.0	1.7	1.0	1.3	0.2	0.8	0.8	0.8	0.8	0.8
LDay ^c	0.2	0.2		2.1	1.8	1.1	1.4	0.3	0.9	0.9	1.0	0.9	0.9
LNight ^a	1.9	2.0	2.1		0.6	1.3	1.1	1.8	1.2	1.2	1.2	1.2	1.2
LNight ^b	1.7	1.7	1.8	0.6		1.3	1.2	1.6	1.0	0.9	0.9	0.9	1.0
LEvening ^a	1.0	1.0	1.1	1.3	1.3		0.4	0.9	0.6	0.7	0.7	0.8	0.7
LEvening ^b	1.3	1.3	1.4	1.1	1.2	0.4		1.2	0.7	0.8	0.8	0.9	0.8
LAeq24h	0.1	0.2	0.3	1.8	1.6	0.9	1.2		0.6	0.7	0.7	0.6	0.6
Lden ^a	0.8	0.8	0.9	1.2	1.0	0.6	0.7	0.6		0.2	0.3	0.3	0.1
Lden ^b	0.8	0.8	0.9	1.2	0.9	0.7	0.8	0.7	0.2		0.1	0.1	0.2
Ldn ^a	0.8	0.8	1.0	1.2	0.9	0.7	0.8	0.7	0.3	0.1		0.1	0.2
Ldn ^b	0.8	0.8	0.9	1.2	0.9	0.8	0.9	0.6	0.3	0.1	0.1		0.2
Ldn ^c	0.8	0.8	0.9	1.2	1.0	0.7	0.8	0.6	0.1	0.2	0.2	0.2	

4.2 Railway noise conversions

Table 7a: Estimated conversion terms between two different noise metrics (cp. Equations (1)-(7b)) for **railway noise**, derived by calculating average differences between metrics at 31'271 dwelling units in Switzerland, in decibels [dB]

	↓ Known metric ↓												
↓ Desired ↓ metric	LDay ^a	LDay ^b	LDay ^c	LNight ^a	LNight ^b	LEvening ^a	LEvening ^b	LAeq24h	Lden ^a	Lden ^b	Ldn ^a	Ldn ^b	Ldn ^c
LDay ^a =		+0.0	+0.1	+0.7	+0.7	-0.4	-0.3	+0.2	-5.9	-6.0	-5.9	-5.5	-5.5
LDay ^b =	+0.0		+0.1	+0.7	+0.8	-0.4	-0.3	+0.2	-5.9	-5.9	-5.9	-5.4	-5.5
LDay ^c =	-0.1	-0.1		+0.6	+0.7	-0.5	-0.3	+0.1	-6.0	-6.0	-6.0	-5.5	-5.6
LNight ^a =	-0.7	-0.7	-0.6		+0.0	-1.1	-1.0	-0.5	-6.6	-6.7	-6.6	-6.2	-6.2
LNight ^b =	-0.7	-0.8	-0.7	+0.0		-1.1	-1.0	-0.6	-6.7	-6.7	-6.6	-6.2	-6.2
LEvening ^a =	+0.4	+0.4	+0.5	+1.1	+1.1		+0.1	+0.6	-5.5	-5.6	-5.5	-5.1	-5.1
LEvening ^b =	+0.3	+0.3	+0.3	+1.0	+1.0	-0.1		+0.4	-5.7	-5.7	-5.6	-5.2	-5.2
LAeq24h =	-0.2	-0.2	-0.1	+0.5	+0.6	-0.6	-0.4		-6.1	-6.1	-6.1	-5.6	-5.7
Lden ^a =	+5.9	+5.9	+6.0	+6.6	+6.7	+5.5	+5.7	+6.1		+0.0	+0.0	+0.5	+0.4
Lden ^b =	+6.0	+5.9	+6.0	+6.7	+6.7	+5.6	+5.7	+6.1	+0.0		+0.1	+0.5	+0.5
Ldn ^a =	+5.9	+5.9	+6.0	+6.6	+6.6	+5.5	+5.6	+6.1	+0.0	-0.1		+0.4	+0.4
Ldn ^b =	+5.5	+5.4	+5.5	+6.2	+6.2	+5.1	+5.2	+5.6	-0.5	-0.5	-0.4		+0.0
Ldn ^c =	+5.5	+5.5	+5.6	+6.2	+6.2	+5.1	+5.2	+5.7	-0.4	-0.5	-0.4	+0.0	

Table 7b: Standard uncertainties (standard deviations) of estimated conversion terms for railway noise, in decibels [dB]

	↓ Known metric ↓												
↓ Desired ↓ metric	LDay ^a	LDay ^b	LDay ^c	LNight ^a	LNight ^b	LEvening ^a	LEvening ^b	LAeq24h	Lden ^a	Lden ^b	Ldn ^a	Ldn ^b	Ldn ^c
LDay ^a		0.0	0.1	1.7	1.6	0.2	0.3	0.5	1.1	1.2	1.2	1.2	1.3
LDay ^b	0.0		0.1	1.6	1.5	0.2	0.3	0.4	1.1	1.1	1.1	1.2	1.3
LDay ^c	0.1	0.1		1.7	1.6	0.3	0.4	0.5	1.2	1.2	1.2	1.3	1.4
LNight ^a	1.7	1.6	1.7		0.1	1.4	1.3	1.2	0.5	0.5	0.5	0.4	0.4
LNight ^b	1.6	1.5	1.6	0.1		1.3	1.2	1.1	0.4	0.4	0.4	0.3	0.3
LEvening ^a	0.2	0.2	0.3	1.4	1.3		0.1	0.2	0.9	0.9	0.9	1.0	1.1
LEvening ^b	0.3	0.3	0.4	1.3	1.2	0.1		0.1	0.8	0.8	0.8	0.9	0.9
LAeq24h	0.5	0.4	0.5	1.2	1.1	0.2	0.1		0.7	0.7	0.7	0.8	0.8
Lden ^a	1.1	1.1	1.2	0.5	0.4	0.9	0.8	0.7		0.0	0.0	0.1	0.2
Lden ^b	1.2	1.1	1.2	0.5	0.4	0.9	0.8	0.7	0.0		0.0	0.1	0.1
Ldn ^a	1.2	1.1	1.2	0.5	0.4	0.9	0.8	0.7	0.0	0.0		0.1	0.1
Ldn ^b	1.2	1.2	1.3	0.4	0.3	1.0	0.9	0.8	0.1	0.1	0.1		0.1
Ldn ^c	1.3	1.3	1.4	0.4	0.3	1.1	0.9	0.8	0.2	0.1	0.1	0.1	

4.3 Aircraft noise conversions

Table 8a: Estimated conversion terms between two different noise metrics (Equations (1)-(7b)) for aircraft noise, calculated from average hourly traffic shares of 48 large (> 50'000 annual movements) European and US airports, in decibels [dB]

	↓ Known metric ↓												
↓ Desired ↓ metric	LDay ^a	LDay ^b	LDay ^c	LNight ^a	LNight ^b	LEvening ^a	LEvening ^b	LAeq24h	Lden ^a	Lden ^b	Ldn ^a	Ldn ^b	Ldn ^c
LDay ^a =		+0.0	-0.2	+7.6	+7.8	+0.0	+0.6	+1.3	-2.3	-2.2	-1.9	-1.2	-1.2
LDay ^b =	+0.0		-0.2	+7.6	+7.8	+0.0	+0.6	+1.3	-2.3	-2.1	-1.9	-1.2	-1.2
LDay ^c =	+0.2	+0.2		+7.8	+7.9	+0.2	+0.7	+1.5	-2.1	-2.0	-1.7	-1.0	-1.1
LNight ^a =	-7.6	-7.6	-7.8		+0.1	-7.6	-7.1	-6.3	-9.9	-9.8	-9.5	-8.8	-8.9
LNight ^b =	-7.8	-7.8	-7.9	-0.1		-7.8	-7.2	-6.4	-10.1	-9.9	-9.7	-8.9	-9.0
LEvening ^a =	+0.0	+0.0	-0.2	+7.6	+7.8		+0.6	+1.3	-2.3	-2.1	-1.9	-1.2	-1.2
LEvening ^b =	-0.6	-0.6	-0.7	+7.1	+7.2	-0.6		+0.7	-2.9	-2.7	-2.5	-1.8	-1.8
LAeq24h =	-1.3	-1.3	-1.5	+6.3	+6.4	-1.3	-0.7		-3.6	-3.5	-3.2	-2.5	-2.5
Lden ^a =	+2.3	+2.3	+2.1	+9.9	+10.1	+2.3	+2.9	+3.6		+0.2	+0.4	+1.1	+1.1
Lden ^b =	+2.2	+2.1	+2.0	+9.8	+9.9	+2.1	+2.7	+3.5	-0.2		+0.2	+1.0	+0.9
Ldn ^a =	+1.9	+1.9	+1.7	+9.5	+9.7	+1.9	+2.5	+3.2	-0.4	-0.2		+0.7	+0.7
Ldn ^b =	+1.2	+1.2	+1.0	+8.8	+8.9	+1.2	+1.8	+2.5	-1.1	-1.0	-0.7		+0.0
Ldn ^c =	+1.2	+1.2	+1.1	+8.9	+9.0	+1.2	+1.8	+2.5	-1.1	-0.9	-0.7	+0.0	

Table 8b: Combined standard uncertainties of estimated conversion terms for aircraft noise (cp. Section 3.2.3), in decibels [dB]

	↓ Known metric ↓												
↓ Desired ↓ metric	LDay ^a	LDay ^b	LDay ^c	LNight ^a	LNight ^b	LEvening ^a	LEvening ^b	LAeq24h	Lden ^a	Lden ^b	Ldn ^a	Ldn ^b	Ldn ^c
LDay ^a		0.5	1.0	7.2	8.1	2.4	3.2	0.6	2.5	2.2	2.9	2.7	2.6
LDay ^b	0.5		0.9	7.2	8.2	2.3	3.1	0.7	2.7	2.2	3.1	2.9	2.6
LDay ^c	1.0	0.9		7.8	8.7	2.9	3.8	1.4	3.3	2.9	3.7	3.4	3.2
LNight ^a	7.2	7.2	7.8		4.4	6.5	5.6	6.7	5.3	5.3	4.9	5.4	5.1
LNight ^b	8.1	8.2	8.7	4.4		7.9	7.2	7.8	6.3	6.8	6.0	6.2	6.7
LEvening ^a	2.4	2.3	2.9	6.5	7.9		1.3	2.4	3.1	2.5	3.5	3.5	3.1
LEvening ^b	3.2	3.1	3.8	5.6	7.2	1.3		3.0	2.8	2.4	3.2	3.3	2.9
LAeq24h	0.6	0.7	1.4	6.7	7.8	2.4	3.0		2.0	1.7	2.4	2.2	2.0
Lden ^a	2.5	2.7	3.3	5.3	6.3	3.1	2.8	2.0		1.3	0.6	0.6	1.2
Lden ^b	2.2	2.2	2.9	5.3	6.8	2.5	2.4	1.7	1.3		1.5	1.6	0.7
Ldn ^a	2.9	3.1	3.7	4.9	6.0	3.5	3.2	2.4	0.6	1.5		0.6	1.3
Ldn ^b	2.7	2.9	3.4	5.4	6.2	3.5	3.3	2.2	0.6	1.6	0.6		1.4
Ldn ^c	2.6	2.6	3.2	5.1	6.7	3.1	2.9	2.0	1.2	0.7	1.3	1.4	

5 Discussion

5.1 Strengths and limitations

In the present exercise, we aimed at deriving widely applicable conversion terms between the most common noise metrics. In the pursuit of this goal, we relied on data about the diurnal variation of road traffic volumes in several European countries, on current detailed noise exposure data in Switzerland for road, rail and air traffic, and on data about the diurnal distribution of air traffic at large European and US airports. While the conversion terms for road traffic noise have been derived based on traffic data in countries of Western Europe only, we regard it feasible to extend the range of application of the presented conversion terms to any country with comparable vehicle fleet composition and mobility behavior. While the operational input data for the Swiss railway noise exposure calculations are very precise for each section of the railway network, it is in the nature of things that the conversions we provide basically account for the average rolling stock mix and timely pattern of the track use by passenger and freight trains in Switzerland. One needs to be aware that the bespoke parameters could be different in other countries. However, to facilitate the extrapolations of conversion rules for road traffic and railway noise to other geographical regions, we employed a highly stratified and balanced sampling strategy of dwelling units in Switzerland as part of the noise-exposure method. While a purely random sample would rather have reproduced the conditions in Switzerland, the highly stratified sampling approach realized here lends itself for a more generic application of the derived conversion rules. Strikingly, for conversions between L_{den} and L_{dn} we found the conversion terms in the present study compared with conversion terms published more than 15 years ago (European Commission, 2002b; Miedema and Oudshoorn, 2001) to be in a range of fractions of a decibel for all sources. As this is very small, we conclude that previous rules of thumb which already have attained a certain diffusion, very well match the corresponding relationships between metrics that we found with more recent data.

To our knowledge, this is the first study to systematically include estimations of uncertainty of differences between noise metrics, allowing a researcher to decide on more solid ground, if to use a particular conversion term or not. For most of the conversions regarding road traffic or railway noise, the order of magnitude of the (combined) standard uncertainty is below 1.5 dB and thus smaller than average uncertainties of noise exposure calculations themselves. However, uncertainty might have been underestimated in the case of road traffic noise conversions. Because in road traffic noise modeling, traffic volume data at a given receiver point are usually simply up- or downscaled to reflect the exposure during different periods of the day, one can generally expect a higher correlation (thus less uncertainty) between metrics from calculated exposure than would be observed with measured exposure, e.g. in 1-hour time slices. Further uncertainty in the case of aircraft noise conversions comes from the fact that the traffic share method, as we used it, assumed (for the sake of simplicity) a constant aircraft fleet mix across the day, although this is probably not the case in the real world.

As mentioned before, the uncertainty of exposure calculations carried out for the loudest facade point is smaller than that at other facade points. This leaves the question for which exposure range the conversion rules are suitable and whether the uncertainty of conversion terms increases at lower exposures. For road traffic (Table 6a) and aircraft noise (Table 8a) the answer is clear: As no acoustic calculations are involved in the determination of the conversion terms themselves (but just

for estimating the combined uncertainty), the conversion terms can be applied to any range. For railway noise, it is very difficult to estimate if uncertainty increases at lower noise levels. There are several unknowns that might play a role, e.g. whether diurnal distributions of traffic volumes are systematically different between low noise exposure and high noise exposure situations, just to name one example. While a certain dependence of uncertainty from exposure level cannot not be completely ruled out, the effect on the accuracy or appropriateness of a conversion in a given case is probably small.

The conversion terms for road traffic noise (Table 6a) are basically derived from AADT data gathered from traffic counting networks. As such are usually installed along national highways and busy roads, the traffic share method is particularly susceptible to underestimate the day-night difference on smaller streets. This is because generally, the traffic flow on highways decreases less during the night time compared to normal roads and city streets. Therefore the level differences between day and night metrics in Table 6a might be a bit larger for less busy streets than indicated.

Lastly, it applies to all noise sources, that across a larger sample of receiver points, the conversion terms under- or overestimate the "true" value of the target noise metric in a non-systematic random fashion (called random non-differential error in epidemiology), which compromises the strength of modelled exposure-effect relationships based on converted exposure data, e.g. in a meta-regression, but does not affect the direction of the effect.

5.2 Practical advice for the application of the conversion terms

The intention of the present exercise was to transparently derive often demanded "rules of thumb" to estimate the value of one (unknown) noise metric, given the value of another (known) metric. These rules of thumb are of course very general. The conversion terms represent generic averages, which not necessarily reflect the precise relationship between two noise metrics for an individual receiver. However, they still reflect the most likely estimate of that relationship if no other information to derive the true relationship is at hand. This said, the conversion terms are applicable in rather generic cases, i.e. where a researcher (e.g. an epidemiologist) has only reduced information about the exact nature and the circumstances of the measurement or calculation of a given noise exposure value that needs to be converted. A typical case would be the carrying out of meta-analyses of original studies.

Among the caveats to consider when using the conversion terms are the following: First and foremost, it is important to stress that all conversions for aircraft noise have a four to five times higher uncertainty than conversions for road- and railway noise. The main reason for this is that airports are on one hand "more different" between each other in their temporal distribution of aircraft movements, than are streets (or railway lines), and secondly, because the routing of in- and outbound flights of an airport is much more complex than the routing of vehicles on a street or of trains on a railway track. Thus, the aircraft noise conversions may work rather precisely for one specific receiver point at one particular airport, while they do not at another receiver point at the same airport.

For road traffic noise conversions, we generally advocate to use Table 6a which more or less represents average Western European conversion terms. Of course, Table 1 and Equation 8 can also directly be used to determine country-specific conversion terms for Switzerland, Germany, Belgium (Flanders), the Netherlands, the UK, or France (Île-de-France) respectively.

Regarding railway noise, the presented conversion terms reflect the situation from 2011, where still many freight wagons in Europe were equipped with cast iron brakes being responsible for high noise emissions. This will change in the future with more and more such wagons receiving so-called K- or L-block or even disc brakes.

A widespread pattern in many European countries is that freight trains use the available railway tracks more intensely at nighttime. As passenger trains generally emit less noise than freight trains, the difference between day and night metrics is considerably smaller than for road traffic noise (cp. Table 7a). In some cases, railway noise exposure can even be higher at nighttime than during day. It is well possible that this pattern and hence the conversion terms derived in Switzerland are rather typical for countries with high shares of international goods transit, like e.g. the Netherlands, Germany, Austria, or Switzerland, to name just a few, but probably less so for peripheral regions, like e.g. Ireland or Portugal, or countries where freight trains presumably run on their own tracks or on tracks with only minor passenger traffic (e.g. USA). If such circumstances are to be assumed in a given case, the conversions for railway noise need to be applied with caution and the day-night difference is probably larger than reported in the conversion terms here.

The presented conversion rules are comprehensive and consider all sub-variants of noise exposure metrics as commonly used today. In particular, we included all the different (country specific) definitions of Ldn and Lden. If the exact specification of the variant of the Ldn and Lden metric is unknown in a given conversion case, we recommend to use the most common variant, this is the Ldn^a (Equation 6a) and Lden^b (Equation 7b).

Finally, we advise to not use any of the conversion terms if the noise exposure situation whose exposure values are to be converted is rather special, e.g. noise of railway cargo from and to a coal mine or similar industry, or noise from a military airfield.

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Conflicts of interest

The authors declare no conflicts of interest.

6 References

- Abbott, P.G., Nelson, P.M., 2002. Converting the UK traffic noise index LA10,18h to EU noise indices for noise mapping. Environment Group of TRL Limited.
- Brink, M., Pieren, R., Foraster, M., Vienneau, D., Eze, I., Schaffner, E., Hritier, H., Cajochen, C., Probst-Hensch, N., Roosli, M., Wunderli, J.M., 2016. Do short-term temporal variations of noise exposure explain variance of noise annoyance?, INTER-NOISE 2016, Hamburg
- Bundesamt fr Umwelt, 2009. SonBase – The GIS Noise Database of Switzerland. Technical bases [English version], Environmental studies Nr. 0908 E. Bundesamt fr Umwelt, Bern.
- Bundesanstalt fr Straenwesen, 2015. Automatische Zhlstellen auf Autobahnen und Bundesstraen (<http://www.bast.de/DE/Verkehrstechnik/Fachthemen/v2-verkehrszaehlung/Stundenwerte.html?nn=626916>),.
- Department for Transport, 2015. Statistical data set Average annual daily flow and temporal traffic distributions (TRA03) (<https://www.gov.uk/government/statistical-data-sets/tra03-motor-vehicle-flow>),.
- Deutsches Zentrum fr Luft- und Raumfahrt, 1999. Bewertung und Berechnung von Fluglrm (FE-Nr. L-2/96-50144/96).
- Direction des routes le-de-France (<http://www.enroute.ile-de-france.developpement-durable.gouv.fr/les-comptages-a174.html>), 2011. Les comptages
- Empa, 2010. FLULA2, Ein Verfahren zur Berechnung und Darstellung der Fluglrmbelastung. Technische Programm-Dokumentation (FLULA2, a Method for the Calculation and Illustration of Aircraft Noise Exposure. Technical Program Documentation). Version 4, Dbendorf.
- Environmental Protection Agency (EPA), 1974. Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety (EPA Report No. 550/9-74-004). Environmental Protection Agency, Washington.
- EUROCONTROL, 2017. STATFOR Interactive Dashboard (SID). Statistics and Forecast Service (STATFOR), EUROCONTROL, Brussels, Belgium. URL: www.eurocontrol.int/statfor.
- European Commission, 2002a. Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise
- European Commission, 2002b. Position paper on dose response relationships between transportation noise and annoyance.
- European Commission, 2015. Commission Directive (EU) 2015/996 of 19 May 2015 establishing common noise assessment methods according to Directive 2002/49/EC of the European Parliament and of the Council. Official Journal of the European Union 58.
- European Environmental Agency, 2010. Good practice guide on noise exposure and potential health effects [EEA Technical report No 11/2010].
- ISO/IEC, 2008. Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995). Guide 98-3 (International Organisation for Standardization (ISO) and International Electrotechnical Commission (IEC), Geneva, Switzerland).
- Miedema, H., Oudshoorn, C., 2001. Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals. Environmental Health Perspectives 109, 409-416.
- Naish, D., Tan, A.C.C., Demirbilek, F.N., 2011. A review of road traffic noise indicators and their correlation with the LA10(18hour), ACOUSTICS 2011, Gold Coast, Australia
- Pietrzko, S., Hofmann, R.F., 1988. Prediction of A-Weighted Aircraft Noise Based on Measured Directivity Patterns. Applied Acoustics 23, 29-44.
- Rosli, M., Vienneau, D., Foraster, M., Eze, I., Hritier, H., Schaffner, E., Thiesse, L., Rudzik, F., Pieren, R., Habermacher, M., Kpfli, M., Brink, M., Cajochen, C., Wunderli, J.-M., Probst-Hensch, N., 2017. Short and Long Term Effects of Transportation Noise Exposure (SiRENE): an interdisciplinary approach [Mini-Symposium], 12th ICBEN Congress on Noise as a Public Health Problem, Zurich
- Schffer, B., Btikofer, R., Plss, S., Thomann, G., 2011. Aircraft noise: Accounting for changes in air traffic with time of day. Journal of the Acoustical Society of America 129, 185-199.

- Umweltbundesamt, 1984. Vergleich nationaler und internationaler Fluglärmbewertungsverfahren Aufstellung von Näherungsbeziehungen zwischen den Bewertungsmaßen (Forschungsbericht 81-105 01 307, UBA-FB 82-025).
- van den Berg, F., 2008. Criteria for wind farm noise: Lmax and Lden, EURONOISE 2008, Paris.
- Wunderli, J.M., Pieren, R., Habermacher, M., Vienneau, D., Cajochen, C., Probst-Hensch, N., Rösli, M., Brink, M., 2016. Intermittency ratio: A metric reflecting short-term temporal variations of transportation noise exposure. *J Expo Sci Environ Epidemiol* 26, 575-585.

7 Figure Captions

Figure 1: Theoretical level differences between selected noise metrics depending on night time traffic share for a constant mix of vehicles, vehicle routing and atmospheric conditions. Calculations are based on a 8-hour night period and the noise metrics definitions given in Section 3.1.

Figure 2: Diurnal distribution of the percentage of the annual average daily road traffic (AADT), measured at 307 automatic traffic counting stations in the year 2011. Boxes represent the interquartile range and the whiskers show values inside $\pm 1.5 \times$ box length, circles are outliers within ± 1.5 to $3.0 \times$ box length, and stars are extreme values outside $3.0 \times$ box length.

Figure 3: Average acoustic energy emitted by road traffic noise by hour of the day, in several European countries, including the mean (dashed line) across all countries. The data series are based on diurnal distributions of traffic counts, including a weighting of the respective average proportion of vehicle pass-by events by light or heavy vehicles.

Figure 4: Scatterplots of $250 \text{ m} \times 250 \text{ m}$ mesh grid points of LNight^a regressed on LDay^a of the Swiss airports Zurich (ZRH, left) and Geneva (GVA, right) including the regression lines and 95% prediction intervals.

Figure 5: Left: Diurnal distribution of the percentage of the annual average daily air traffic (AADT) from 48 selected airports with $>50'000$ annual movements, averaged over all available data-years per airport. Boxes represent the quartiles and the whiskers show values inside $\pm 1.5 \times$ box length, circles are outliers within ± 1.5 to $3.0 \times$ box length, and stars are extreme values outside $3.0 \times$ box length; Right: AADT, plotted separately for the sampled 28 European and 20 US airports (mean values plus standard error bars), including the corresponding figures for EU-EFTA airports (EUROCONTROL, 2017) (mean value of 2013–2015).

Figure 6: Noise maps of Switzerland showing road (left) and railway traffic (right) Lden in the year 2011. Blue dots represent the locations of dwelling units (in total: 52'030) that were used in the present exercise.

Lden Road Traffic

Lden Railway