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DOES AN INDIVIDUALISATION OF STANDARD MAKE SENSE?

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ABSTRACT

Roadway noise is a major contributor to the overall environmental noise pollution. Whilst the sound emission of roads is determined by factors like number and type of vehicles, their respective speed or road surface type, the sound propagation and immission is strongly influenced by environmental and meteorological conditions. Several norms are currently in use for the prediction of sound levels along roads. However, many of them, including the German norm, compute the sound pressure levels under the assumption of standard meteorological conditions that might not be representative for individual sites. The aim of this work is, without fundamentally redesigning the standard, to use meteorological parameters in such a way that correction factors can be determined depending on the conditions. Based on long-term measurements of noise immission and meteorology at different locations, supplemented by simulations with a wave- based model, eight damping classes were defined for a total of 60 possible meteorological situations, thus allowing an individual correction of standard calculations. The newly proposed method shows significant improvements in the predicted sound pressure level, in particular for sites with medium to high downwind-conditions.

Keywords: *outdoor sound propagation, roadside noise, RLS-90, RLS-19*

1. INTRODUCTION

In 2002 the European Commission released the Environmental noise directive 2002/49/EC, by requiring Member States to draw up 'strategic noise maps' for major roads, railways, airports and agglomerations, using harmonised noise indicators. Outdoor sound propagation, and therefore also roadside noise, is influenced by various parameters. These include meteorological and topographic conditions as well as soil characteristics, plant coverage and buildings, but also the source characteristics like frequency composition and source type (point source, line source, etc.) play an important role. Whilst most of these parameters are included in the majority of sound propagation models, the situation is more divers with respect to meteorology. There are several, national as well as international standards that, to some extend, included meteorological effects into their computations. Some standards, like Nord2000 or *HARMONOISE* consider several different sound propagation conditions, others, like Cnossos, only distinguish favourable and non-favourable conditions. In Germany the RLS-90/RLS-19 (Guidelines for Noise Protection at Roads [1], [2] is used to predict sound pressure levels near roads. It does not take into account different meteorological conditions but assumes slightly favourable sound propagation conditions.

Considering the standard's main purpose which is resident protection, this goal is met in most of the cases, as generally, the meteorological conditions lead to a mix of favourable and non-favourable sound propagation conditions and therefore an over-prediction of the expected noise level. However, there are sites, in particular in northern Germany, where significantly favourable propagation conditions prevail. In these particular cases, the standard can fail to predict an upper limit to the actual sound pressure conditions, leading to insufficient noise protection of residents.

The goal of this work is to quantify the effects of the most relevant meteorological parameters in context with roadside noise and develop a parameterised model for the optional consideration of different meteorological situa-

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tions within the existing standard. An overview on the findings of this work can be found in [3]. In the future this new tool can be utilised for the calculation of more realistic noise predictions for sites with predominantly favourable or questionable sound propagation conditions.

As will be seen in section 2, high-resolution noise and meteorology data are needed to accomplish this goal. To obtain a data-set that fulfils all the requirements, regarding temporal resolution as well as external conditions, a 3-month measurement campaign was carried out along a motorway north-west of Munich. These measurements included noise and meteorological data and were supplemented by road traffic measurements and weather model data. In section 3 we will briefly describe the data aggregation and evaluation process. Using a split-apply-combine approach, the data were filtered by different meteorological parameters and the individual situations were analysed with respect to neutral sound propagation conditions. Section 4 concentrates on the development of the actual model. Afterwards, the model was validated using the given data. Finally, all findings are summarised in section 5 where also an outlook on future work will be given.

2. MEASUREMENTS AND DATA COLLECTION

For this project we rely on a large sample of input data, to include all possible conditions of noise nuisances. Besides extensive noise measurements, the relevant data are traffic volume and the local and global weather conditions. In the following, an overview on the measurement site and the collected data is given.

The measurement site itself was chosen based on a number of constraints like flat topography to minimise influence of terrain, traffic-monitoring-stations nearby to calculate emission sound pressure levels and a motorway that is approximately perpendicular to the main wind direction with well defined downwind/upwind conditions. Moreover we were looking for a site that is free of obstacles like houses, bushes, trees, etc. in order to avoid sound reflection and/or absorption with negligible background noise at least most of the times. Finally, as measurements were carried out over the course of three month power supply and infrastructure for the monitoring stations had to be available. Based on these constraints the motorway BAB A8 was chosen, where the site was slightly south of Sulzemoos (between Munich and Augsburg). Within the site area there is a small location with a farm from which electricity for the operation of the monitoring stations could

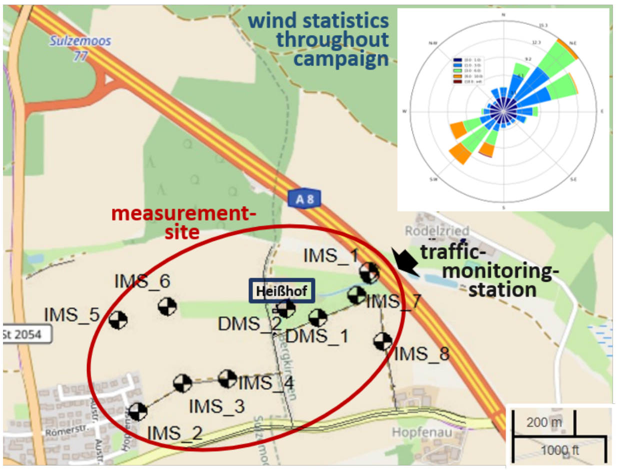

Figure 1. Distribution of monitoring stations on site. "DMS" refers to a monitoring station that was used throughout the whole campaign, whereas "IMS" describes a station that was operational only in selected weather conditions.

be received. Fig. 1 gives an overview of the terrain, the measurement site and the traffic-monitoring-station. The terrain is mostly flat, with some smaller elevations of few meters of heights.

All measurement positions that were used throughout the campaign are indicated, where the prefix "DMS" refers to a monitoring station that was used throughout the whole campaign, whereas "IMS" describes a station that was operational only in selected weather conditions. In the upper right corner the wind direction statistics, measured locally throughout the campaign are shown. One of the long term measurement stations ("DMS") is shown in Fig. 2.

Concerning the meteorological data we concentrated on three parameters which are the stability of the atmosphere up to 200m of height, wind-speed and wind-direction. Whilst the stability of the atmosphere was estimated from COSMO-DE model data, wind-speed and wind-direction – due to their high fluctuation – need to be known locally and with a high temporal resolution, and were therefore measured on-site with 1 Hz resolution in case of station "DMS_2" and with 10 Minutes resolution in case of station "DMS_1". As frozen as well as snow covered ground change the sound propagation conditions due to elevated and reduced reflection, respectively, we excluded all data

Figure 2. One of the long term measurement stations ("DMS") that is located about 250m away from the motorway.

measured under these conditions. Furthermore we also excluded all periods of rain, as a wet road surface alters the characteristic sound frequencies of roadside noise.

The traffic volume is monitored on several stations by the Federal Highway Research Institute - BASt along German highways. Traffic data were provided by the motorway authority for southern Bavaria (Autobahndirektion Südbayern) in 1 minute resolution. Those data included vehicle type (car, truck), total number of vehicles and number of trucks per lane as well as the average speed per lane for both, cars and trucks.

The measurements were carried out over a period of 3 month, starting at 14.09.2018 and ending at 14.12.2018.

3. DATA ANALYSIS

A typical approach in noise analysis is data averaging, leading to noise indicators that can be handled easily but at the expense of loosing many information. While this can be even desirable e.g. in judging the average exposure to noise, it is not suitable to understand the underlying physical processes. By filtering our data with respect to different meteorological parameters we create clusters with similar sound propagation conditions. By averaging the data within individual clusters we can then compare the sound propagation for different meteorological situations.

In this section we combine the different data sources to describe the various sound generation and sound propagation scenarios. First, we are introducing the classification of the meteorological data and having a quick look at the respective statistics. Afterwards, the traffic data is analysed and it will be shown, how the sound emission level can be computed from those data. Finally we will analysis of sound measurements under consideration of both, meteorological and traffic data.

3.1 Classification and Evaluation of Meteorological Parameters

For each of the meteorological parameters, a classification, suitable to capture their effects on sound propagation, was defined. These classes are explained more in detail in the following.

Like in the *HARMONOISE* norm, five stability-classes were defined but instead of using daytime and cloud coverage, the classification was carried out using temperature profiles from COSMO-DE data. These stability-classes were determined from the temperature profile between $10m$ and $200m$ of height above ground level, ranging from S_1 (unstable) to S_5 (very stable) where S_3 refers to the isothermal profile which is the neutral profile from an acoustics point of view. In table 1 the criteria for the five stability classes are summarised. Five wind-speed-classes are defined based on *HARMONOISE* however, one additional class for was defined for (nearly) zero wind conditions, and due to the lack of data for higher wind speeds, all wind speeds larger than $6.0m/s$ are summarised in class W_4, meaning class W_5 as it is defined in *HARMONOISE* was neglected. The classification is shown in table 2. The splitting of the original class W_1 into a class W_0 and a modified class W_1 was chosen based on our data where no wind-direction dependency is found for wind speeds less then $0.2m/s$, in contrast to wind speeds above this limit. Therefore, in class W_0, sound propagation is only influenced by the vertical temperature profile but not by a wind speed gradient.

The wind direction is split in classes that cover 22.5° each, centred at 0° , where the measurement region was rotated such that 0° refers to tail- and 180° to headwind, i.e. all together there are 16 wind direction classes D_1 to D_{16} with $D_1 = [348.75, 11.25[$.

The measurement site is dominated by low wind speeds; more than 85% of the data fall into classes W_1 and W_2 $(0.2 - 3m/s)$, 11.1% account for class W_3, while classes W_0 and W_4 in total are only 3.6%.

3.2 Evaluation of Traffic Data using the RLS-90 standard

Traffic data were provided by the motorway authority for southern Bavaria (Autobahndirektion Südbayern) in 1 minute resolution, including vehicle type (car, truck), total

Table 1. Definition of the wind speed classes based on *HARMONOISE*. Range is given in K/100 m.

class	S_1	S_2	S_3	S_4	S_5
range	<-0.8	[-0.8,-0.25[	[-0.25, 0.25[	[0.25, 1[	$\geq$ 1

class	W_0	W_1	W_2	W_3	W_4
range	$[0, 0.2[$	$[0.2, 1[$	$[1, 3[$	$[3, 6[$	≥ 6

Table 2. Definition of the wind speed classes based on *HARMONOISE*. Range is given in m/s.

number of vehicles and number of trucks per lane as well as the average speed per lane for both, cars and trucks. In order to compute the emission sound level from our data, the German national standard for the computation of road traffic noise – RLS-90 – was used.

Following RLS-90, the emission- and immission sound pressure level can be predicted either using representative measurements of hourly traffic intensity and truck ratio, or by using daily traffic averages from which the latter two can be deduced via a table (taking into account road type and time period).

Here, we are interested only in the emission sound level $L_{m,E}$ which, in accordance with RLS-90, is computed as follows:

$$L_{m,E} = L_m + D_v \tag{1}$$

where L_m denotes the average sound level in dB and, in this case, is valid under the following assumptions: the horizontal distance (to the middle of the road) is 25 m, the road surface is ungrooved mastic asphalt, the maximum permitted speed is 100 km/h and the gradient of the road is $\leq 5\%$.

In our case, no correction terms for road gradient, road surface or reflections are needed. For M and p being the total number of vehicles per hour and the ratio of trucks, respectively, we have

$$L_m = 37.5 + 10\log_{10}(M(1 + 0.082p)). \tag{2}$$

For roads with more than one traffic lane, M has to be divided by two in order to represent the two outermost lanes of the road. Then, two average sound levels, $L_{m,n}$ (nearest lane) and $L_{m,f}$ (furthest lane), have to be computed and are averaged in the sense of an energetic mean:

$$L_m = 10\lg\left[10^{0.1L_{m,n}} + 10^{0.1L_{m,t}}\right]. \tag{3}$$

D_v, D_{str} and D_{stg} denote the corrections for velocity, road surface and road inclination in case they differ from the above assumptions. Letting L_c and L_t be the average sound levels for 1 car/min and 1 truck/min, respectively, and v_c and v_t the maximum permitted velocities for cars and trucks, we have:

$$D_v = L_c - 37.3 + \\ + 10\lg\left(\frac{100 + \left(10^{0.1D} - 1\right)p}{100} + 8.23p\right), \tag{4}$$

$$L_c = 27.7 + 10\lg(1 + (0.02v_c)^3), \tag{5}$$

$$L_t = 23.1 + 12.5\lg(v_t), \tag{6}$$

$$D = L_t - L_c. \tag{7}$$

In the present case, no corrections for road surface and gradient had to be applied. Instead of using the standard 1-hour averages, we computed emission sound pressure levels with one minute resolution.

3.3 Analysis of sound measurements under consideration of meteorology and traffic data

In order to analyse the influence of different meteorological conditions on the sound pressure level we first need normalised, i.e. traffic-independent data. This is achieved making use of the fact that the difference ΔL between sound pressure levels, measured and/or computed at two different positions does not depend on the emitted sound pressure level but only on the receiver's distance to each other. If for a constant distance, the difference ΔL changes, this must be due to a change in the sound propagation conditions. Knowing the vehicle's number and velocities, we first compute the emission sound pressure levels as described in the previous section and then the differences ΔL of this sound pressure level with the recorded immission sound pressure level. These differences are independent from the actual emission sound pressure level such that all data recorded under the same sound propagation conditions are directly comparable with each other.

The data were then filtered for wind speed and stability and then, for each combination of the two, the dependency of ΔL from the wind direction was evaluated by binning the data in the 16 previously defined wind-direction classes D_i and afterwards computing the average sound pressure level for each D_i. Fig. 3 shows the ΔL, measured

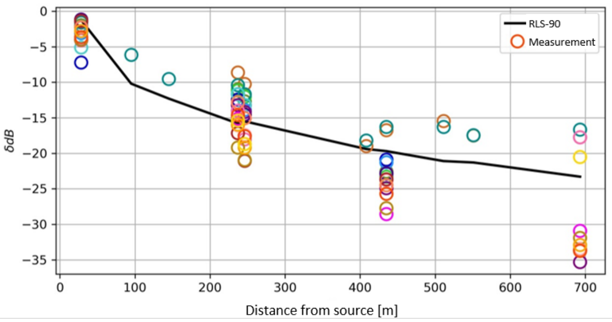

Figure 3. Comparison between the damping following standard calculations (RLS-90) and damping measured in different meteorological situations at different measurement stations (coloured rings, different colours indicate different situations).

during different meteorological situations in comparison with the sound pressure level differences (depending on the distance from the source) following RLS-90.

We then defined a *reference sound pressure level* (RSPL), which is the resulting averaged sound pressure level of the combination W_0/ S_3 (neutral sound propagation conditions), averaged over all wind directions. This RSPL will be used throughout the following evaluation. We will first analyse the influence of wind-direction, wind-speed and stratification for a constant measurement position. Afterwards the sound propagation for distances up to nearly 700m from the source will be analysed for selected meteorological situations. Finally we will also demonstrate the importance and influence of the averaging period or time resolution of the measurements, respectively.

Fig. 4 shows the results of the filtering described above for the two long term measurement positions at distances of about 240m from the source for the wind speed classes W_0, W_1 and W_2.

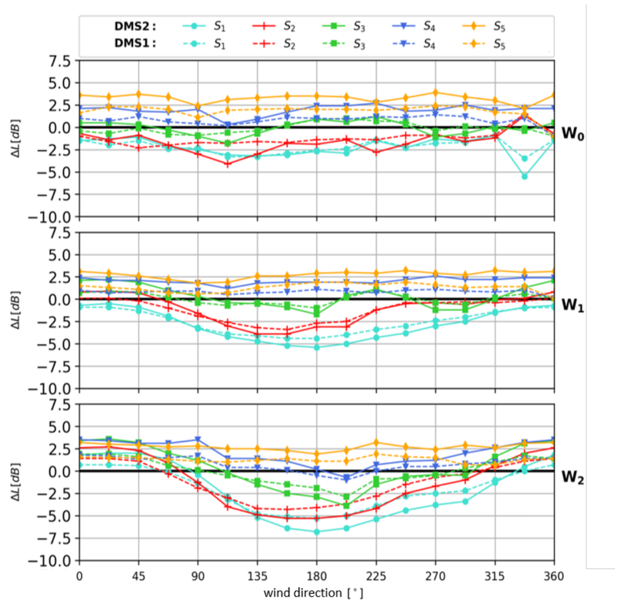

Figure 4. Differences ΔL_1 and ΔL_2 between computed emission sound pressure level and recorded immission sound pressure level for wind classes W_0 (top), W_1 (middle) and W_2 (bottom) for two devices 1 and 2, respectively, are shown. For each wind class the differences for all five stability classes are shown. 0° refers to tailwind (not north!) such that the largest reductions $\Delta L_{1/2}$ are found for 180° (downwind).

1. As can be expected, no wind direction-dependency is found for $\mathbf{W_0}$, but the $\Delta L_{1/2}$ only depend on the stability, where the least strong reductions are found in the most stable case (S_5) and the strongest reductions are found for the most unstable cases (S_1 and S_2).

2. For $\mathbf{W_1}$ we see a clear dependency of $\Delta L_{1/2}$ from the wind direction for S_1 and S_2, whilst this is less evident for S_3 and no dependency is found for S_4 and S_5.

3. In case of $\mathbf{W_2}$ we find that there are already gaps in the data for stability classes S_4 and S_5 and we find a clear dependency of ΔL from the wind direction for S_1 to S_3 and a slight dependency for S_4.

4. MODEL

In the following we are proposing a model that enhances the RLS-90/RLS-19 by a simple parametric equation that allows to consider a total of 8 different damping classes, depending on how favourable or unfavourable a certain situation is. As different combinations of meteorologic parameters can have very similar damping effects, those will be combined within one damping class. Within the standard, the equivalent continuous sound pressure level for a road-section with index i and length l_i is computed as follows:

$$L_{m,i} = L_{m,E} + D_l + D_s + D_{BM_1} + D_B, \tag{8}$$

where $L_{m,E}$ is the emission sound pressure level, D_l is a correction term that accounts for the length of the road-section $D_l = 10\lg(l_i)$, D_s is a term that considers the distance of the immission point from the source as well as air damping and D_B describes the influence of topography and buildings. Finally, D_{BM_1} is the equation that takes into account the effects of ground-absorption and meteorology. The immission sound pressure levels of all road-sections are then added up to the immission sound pressure level L_m:

$$L_m = 10\lg \sum_i 10^{0.1 L_{m,i}}. \tag{9}$$

Hereby, D_{BM_1} itself is defined as follows:

$$D_{BM_1} = \min\left(\frac{h_m}{s}\left(34 + \frac{600}{s}\right) - 4.8, 0\right), \tag{10}$$

where s is the distance between emission and immission point and h_m is the mean height between the ground and the line connecting them.

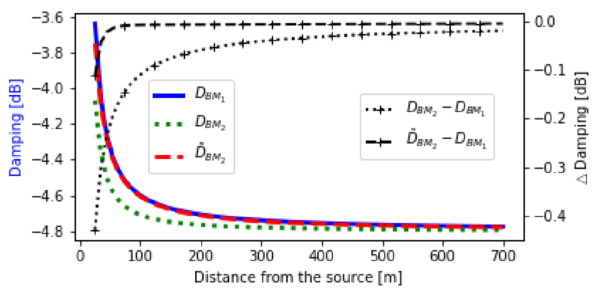

Figure 5. Comparison between different ground and meteorology damping terms.

For our model we will however use a different model for the meteorological and ground damping that is defined as follows:

$$D_{BM_2} = -4.8 \exp\left(-\left[\frac{h_m}{s}\left(8.5 + \frac{100}{s}\right)\right]^{1.3}\right). \tag{11}$$

In the following we will show how D_{BM_2} is adjusted such

damping class	α	β	ξ
p_2	2.0	2.0	2.0
p_1	3.3	7.5	1.3
p_0	4.8	10.0	1.1
m_1	6.7	19.0	0.8
m_2	8.7	32.0	0.7
m_3	12.0	50.0	0.6
m_4	10.0	120.0	0.5
m_5	32.0	225.0	0.4

Table 3. Overview on the parameters α, β and ξ for the damping classes p_2 to m_5.

that it can model meteorological damping for different meteorological situations. We therefore introduce four parameters, α, β, γ and ξ and rewrite (11) as follows:

$$\tilde{D}_{BM_2}(x) = -\alpha \exp\left(-\left[\frac{h_m}{x}\left(\beta + \frac{\gamma}{x}\right)\right]^{\xi}\right). \tag{12}$$

Using numerical optimisation we first calculated the parameters α, β, γ and ξ such that the error between (12) and (10) is minimised, leading to $\tilde{\alpha} = 4.8$, $\tilde{\beta} = 10.0$, $\tilde{\gamma} = 100.0$ and $\tilde{\xi} = 1.1$ (decimal points where restricted to one). By $\tilde{D}_{BM_2}$ we define the damping term D_{BM_2} using the parameters $\tilde{\alpha}$, $\tilde{\beta}$, $\tilde{\gamma}$ and $\tilde{\xi}$ (compare (12)). Fig. 5 shows a comparison between the three different damping terms. One can easily see the good agreement between $\tilde{D}_{BM_2}$ and D_{BM_1}.

Thorough analysis showed that γ should be kept constant with $\gamma = 100.0$. Based on the available data, Nord2000 simulations as well as high-fidelity simulations, the above mentioned 8 damping classes were defined. The according parameters are found in table 3 and an overview on the damping curves for distances from the source between 10 and 700 m is given in Fig. 6. The preliminary classification of meteorological situations into the damping classes is given in table 4. This classification will need

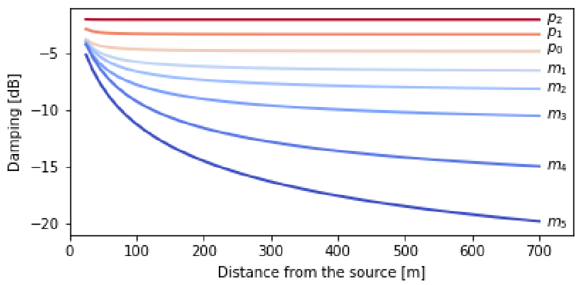

Figure 6. Overview on damping classes p_2 to m_5.

further adjustments in the future, in particular with regard to higher wind speeds. Future work is also dedicated to the validation of the classification at other sites. The corrected immission sound pressure level $\widetilde{L}_m$, specific for a given damping class can now be computed as follows. First, the meteorological situation has to be determined. Second, the damping class assigned to that situation has to be selected from table 4, giving the parameters α, β and ξ that are then inserted in (13):

$$\begin{aligned}\widetilde{L}_m &= L_m + D_{BM_1} + \tilde{D}_{BM_2} = \\ &= L_m + min\left(\frac{h_m}{s}\left(34+\frac{600}{s}\right)-4.8, 0\right) - \\ &\quad - \alpha_{i,j,d} exp\left(-\frac{h_m}{s}\left(\beta_{i,j,d}+\frac{100}{s}\right)^{\xi_{i,j,d}}\right), \quad (13)\end{aligned}$$

where L_m is the standard sound pressure level, the second term is the standard damping term that has to be added back to L_m and the third term is the corrected damping term.

Fig. 7 shows a comparison between calculations (green curve: standard RLS-90 calculations; black curves: RLS-90 with situation-specific damping calculation) and measurements (coloured markers), averaged throughout different meteorological situations. The yellow area indicates the mean variance of measurements which was in the range of ± 6 dB. It should be noted that for higher wind speeds (i.e. W_3 and partially W_2) the measured damping significantly undershoots the calculated values, in particular in the far field. This is caused by wind induced noise, generated directly at the microphone and is particularly pronounced in class m_4, situation S_2W_3GW.

We also computed the mean squared errors between the measurements and both calculation methods, the standard RLS-90 and the adjusted method. The results are shown in Fig. 8, where mse_{rls} indicates the standard method and mse_i the adjusted method. In addition, the difference between the two methods is indicated by the filled ares, where green colour means that the adjusted method performs better than the standard and vice versa for orange colour. In almost all cases the adjusted method works better than the standard method. In class p_0 there is no difference as the damping term of the adjusted method matches the standard method. We find that orange areas (adjusted method worse than standard) correspond to cases with high wind speeds in upwind situations. In these cases the measurements are dominated by wind induces noises and therefore not meaningful to judge the actual damping. All together, the adjusted method leads to significantly better results and in many situations can decrease the error by more than 50%.

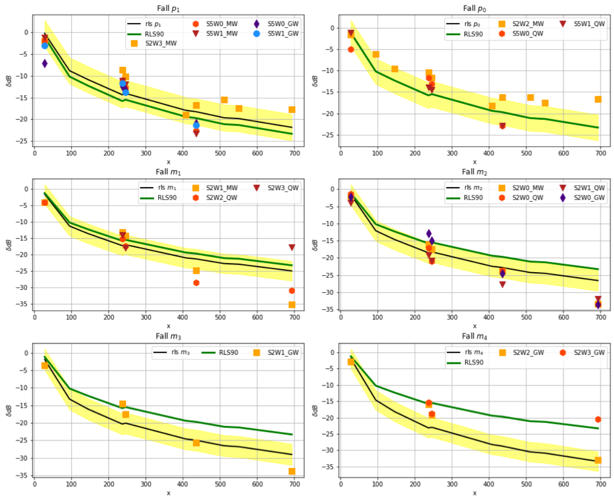

Figure 7. Comparison between calculations and measurements throughout different meteorological situations.

5. CONCLUSION AND OUTLOOK

The weather conditions were divided into classes of wind direction, wind speed and temperature gradient (stability) and their combinations were shown based on the effect on sound propagation. It is consistent, with the help of advanced calculation methods and also the measurements, that the wind direction has the greatest influence on sound propagation, the wind speed (again depending on the direction) has a smaller influence and finally the tempera-

	W_0			W_1			W_2			W_3			W_4		
	dw	sw	uw	dw	sw	uw	dw	sw	uw	dw	sw	uw			
S_1	m_2	m_2	m_2	m_1	m_2	m_3	p_0	m_1	m_4	p_1	m_1	m_4	p_1	–	–
S_3	p_0	p_0	p_0	p_0	m_1	m_1	p_1	m_1	m_2	p_2	p_0	m_3	p_2	–	–
S_5	p_1	p_1	p_1	p_1	p_1	p_1	p_1	p_0	p_0	p_2	–	–	p_2	–	–

Table 4. Preliminary classification of meteorological situations.

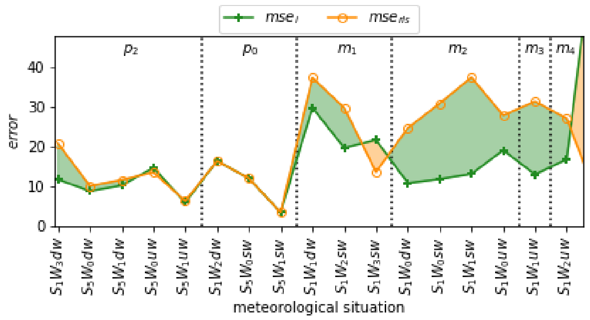

Figure 8. Mean squared errors between measurements and calculation methods, where mse_{rls} indicates the standard method and mse_i the adjusted method.

ture gradient (stability) only at large distances and in conjunction with screening has relevant influences on sound propagation. Based on these results, a proposal for the extension of the RLS-90 / RLS-19 was made, with which the influences of wind and temperature gradients can be taken into account for special considerations in comparison to the normal case of the RLS- 90 / RLS- 19. A calculation of a long-term averaging level is thus also possible in principle, but the associated effort is considerable with regard to the dominance of the conditions favourable for sound propagation. The possibility of considering certain meteorological situations separately is the main intended use of the proposal. Future work will be dedicated to the actual prediction of the sound pressure level based on the meteorological situation and the distance of the receiver from the source.

6. ACKNOWLEDGEMENTS

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