Maximum-level as an additional criterion for the assessment of railway noise at night: Derivation of a wake-up protection criterion for standards and regulations

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Summary
On behalf of the Hessian Ministry of the Environment in Germany, an expert report was prepared to clarify if a maximum level distribution of rail traffic noise at night is more suitable to develop a noise protection concept rather than considering the Equivalent Continuous Sound Level LAeq. In this paper, it is shown that a LAeq alone is not sufficient to adequately describe the noise-induced fragmentation of sleep structure and the strongest physiological response to noise at night, the awakening reaction. At sleep, human beings react to individual events, which are mainly characterized by the number of trains, the maximum level distribution and the train type. These measures are not adequately reflected by the LAeq.

This paper pursues the principle of minimizing acute effects (awakening reactions, reported sleep disturbances and annoyance) so that short-term (fatigue and increased risk of accidents on the following day) and long-term consequences (risk increases for the onset of diseases) do not occur. Analyzes were carried out by means of polysomnographic data being measured in the field study DEUFRAKO / RAPS considering 33 residents à 9 nights each, all living near busy railway tracks in the Middle Rhine Valley. Results were used to determine an exposure-response function for the awakening probability due to a single train noise event TNE. The sum of the awakening probabilities for all individual events result in the additional train noise induced awakening reactions, which are to be limited in a night-time protection concept.

Considering these results together with criteria as derived from survey data on reported sleep disturbances (see Schreckenberg et al.), Möhler et al. will present a combined protection concept for residents affected by train noise at night at this EuroNoise conference. Basic acoustical input data for this concept include maximum level distributions for freight and passenger trains.

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1. Introduction

An undisturbed sleep is important for performance, well-being and health [1]. Noise-induced sleep disorders are usually divided into three categories: "primary effects" refer to the immediate reactions during sleep to a single noise event. These immediate effects of noise can be awakening reactions and are often associated with heart rate accelerations or transitions from deep sleep into light sleep stages. The "secondary effects" describe the resulting consequences on the adjoining day, e.g. daytime tiredness, lack of performance and deficiency in concentration. In the "tertiary effects" one summarizes usually possible health consequences after long-term noise exposure, such as increased risks for high blood pressure, heart attack, overweight or depression. In particular, the relationship between primary and tertiary effects is still unclear, since in addition to noise and the resulting primary effects, a large number of confounders can lead to an increase in these disease risks after many years of exposure to noise. Both, a reliable calculation of the perceived noise over the years as well as an almost complete and accurate recording of the confounders is currently almost impossible. Epidemiological studies describing these tertiary effects therefor must currently be content with approximations. This disadvantage can be partly compensated by averaging over very high numbers of cases. Studies to investigate the acute effects of noise at night, however, are very accurate in measuring the perceived noise and the physiological variables to be examined, but usually can only consider to examine a limited number of subjects due to high study costs and associated budgets.

Schmidt et al. [2] for the first time provided first evidences in such a study on acute effects of nocturnal aircraft noise which potential mechanisms could possibly contribute to the emergence of cardiovascular diseases after many years of noise exposure. Considerable more research efforts in this area are needed in the future in order to understand the effects of long-term noise exposure on health.

The strongest physiological response in human sleep to noise is the awakening reaction and, concomitantly, an increased sleep fragmentation. Effects such as the total number of sleep stages changes are generally less pronounced [3]. In order to develop a protection concept for nocturnal railway noise, it has to be known how often a resident living near railway tracks additionally wakes up due to the number of nightly train passages. A worldwide literature research by the World Health Organization WHO for the years 2000-2014 could only identify one field study with ecologically valid sleep data measured by polysomnography [4]. This was the field study RAPS (Railway Annoyance Performance Sleep) carried out by the German Aerospace Center (DLR) in the years 2006-2010 as part of the German-French research cooperation DEUFRAKO.

Considering the results from the physiological measurements of this DEUFRAKO-RAPS study, presented in this paper, together with criteria as derived from survey data on reported sleep disturbances (see Schreckenberg et al. [5]), Möhler et al. [6] will present a joined protection concept for residents affected by train noise at night at this EuroNoise conference limiting the number of additional train noise induced awakenings and reported sleep disturbance. Basic acoustical input data for this concept include maximum level distributions for freight and passenger trains as well as the average continuous sound pressure levels for the night.

2. Methodology

The field study was operated between February 2008 and July 2009 at residents' places next to the rail tracks from Cologne via Bonn to Erpel in the northern Middle Rhine Valley in Germany which are also highly frequented throughout the night. A total of 33 residents aged 22 to 68 years (mean 36.2 ± 10.3 years, female: n = 22) were examined at 27 different places (6 couples). All subjects were healthy, did not suffer from any intrinsic sleep disorders, and were normally hearing according to their age. The sleeping rooms were between 6 m and 135 m (distance: house wall - closest track) away from the rail traffic (mean: 42 m ±29 m).

Sound pressure levels L_{pAF} and L_{pAS} were measured continuously throughout the night with class 1 sound level meters (NC10, Cortex

Instruments) outside (2 m in front of the bedroom window) and inside (at the sleeper's ear), recording at a sampling rate of 110 ms. As soon as the background level L90 was exceeded by more than 3 dB, the noise event itself was also recorded as a wav file so that a later identification of the noise source (freight / passenger trains, road traffic, neighborhood noise, etc.) could be ensured. All noises that occurred at night at the sleeper's ears were subsequently checked, marked, classified and evaluated in accordance to the German DIN standards, using a software especially developed for these requirements at the German Aerospace Center DLR.

Polysomnography includes the recording of the EEG (electroencephalography = brain activity), the EOG (electrooculography = eye movements) and the EMG (electromyography = muscle activity) for the quantitative and qualitative assessment of sleep. In order to derive polysomnographic parameters, electrodes are glued to the scalp and face at predetermined positions. Thus, the electrical surface activity of the brain in form of potential fluctuations can be continuously recorded. During sleep, amplitude and frequency of the wave patterns in the EEG, the type of eye movements and muscle activity typically change and allow the determination into sleep stages (Awake - light sleep (stages S1 and S2) - deep sleep (stages S3 and S4) - dream sleep (Rapid eye movement (REM) - sleep) The analysis of the sleep data was achieved according to Rechtschaffen and Kales [7], whereby a trained evaluator assigns a sleep stage for every 30-second epoch.

Due to the high staff time and effort, which includes both the application of the electrodes (about 1 h every evening, about ½ h every morning in the field) and the subsequent manual evaluation of sleep and acoustics, the implementation of these field studies is time consuming and expensive. Thus, while the number of subjects studied is naturally limited on the one hand, on the other hand, this study provides data with high ecological validity for the sample of subjects studied.

For a more detailed description of the methodology used in the DEUFRAKO / RAPS study and the descriptive analysis of train movement rates and acoustic measurements, refer to the final report of the study [8], [9].

In addition to the evaluations described in that final report, the sound exposure level SEL of every train noise event TNE, the pass-by exposure level TEL and the probability of spontaneous awakenings were additionally calculated for the present paper. In particular, in the DEUFRAKO-RAPS project no analysis were carried out that took possible contributions to the resident’s awakening probability due to level fluctuations of freight trains passing by into account.

3. Results

In order to find an exposure-response curve that establishes a relationship between the noise exposure and the probability of physiological awakenings, an event-related evaluation is necessary. "Event-related" means that for every train pass by, a statistical check has to be made whether for the current 30s sleep episode or the two epochs after, a transition between sleep stages or stage “awake” can be found. Transitions to light sleep stage "S1" and not only to stage "awake" were considered as “awake” which is a protective approach for the residents. A random effects logistic regression was used to calculate the probability of awakening controlled by the acoustic parameters of the railway noise event [10].

The choice of predictors that were included in the regression model occurred step-wise [11]. The decision as to whether a variable was included or removed in the model was based on the AIC (Akaike Information Criterion). This is a measure for the goodness of fit of a regression model. On the one hand, the AIC rewards the goodness of fit by means of the likelihood function and on the other hand "penalizes" the addition of further predictors [12]. Thus, this penalty prevents an "overfitting" because increasing the number of model parameters usually improves the quality of fit. Lower AIC values mean a better model quality.

A variety of acoustic, personal and situational variables may have a potential impact on the probability of awakening. For the calculation of the exposure-response relationship, the influence

Table I. Example of summands (resulting from median values of the current study), corresponding units and factors for calculating an exposure-response curve.

Summand	*Unit*	*Factor*
$L_{pAF,max}$	dB	---
Total time duration of TNE	s	67 s (Median)
Previously passed sleep duration	min	300 min (Presetting)
Time spent in sleep stage before	min	6.5 min (Median)
$LpAF\_ShortLeq_{01-10}$	dB	0.9 dB (Median)

of the following variables on the quantity of the probability of awakening were examined:

Acoustic parameters (level indoors, measured at the sleeper's ear):

- LpAF,max of the TNE (in dB)
- Sound exposure level SEL of the TNE (in dB)
- Pass-by exposure level TEL of the TNE (in dB)
- Total time duration of TNE (in s)
- Assessment period of the TNE (in s)
- Rise time of the TNE (in dB/s)
- LpAF,eq 1 min before the TNE (in dB, "background level")
- Emergence (LpAF,max minus background level) of the TNE (in dB)
- Number of previous TNE before the start of the considered TNE
- Median of a fluctuation measure describing the TNE (in dB/s^2)
- Mean of a fluctuation measure describing the TNE (in dB/s^2)
- $LpAF\_ShortLeq_{01}$ minus $LpAF\_ShortLeq_{10}$ (in dB)
- $LpAF\_ShortLeq_{01}$ minus $LpAF\_ShortLeq_{20}$ (in dB)
- $LpAF\_ShortLeq_{01}$ minus $LpAF\_ShortLeq_{30}$ (in dB)

Sleep parameters:

- Previously passed sleep duration (in min)
- Sleep stage before the occurrence of the TNE
- Time spent in the sleep stage before the occurence of the TNE (in s)

Personal parameters:

- Gender
- Age

A total of 5,428 undisturbed freight train noise events from 252 nights of 33 subjects were included in the analysis for calculating the probability of awakening for a freight train noise event.

Taking into account the best practice-optimized approximation for a freight train pass by and the calculation of the probability of spontaneous awakenings, the following equation results for the calculation of the probability of awakening for a freight train pass by:

$$A_{FT}=0.02612*L_{pAF,max} - 0.0045479*time_{FT} + 0.000673*time_{AFA} - 0.0119262*time_{CST} + 0.1103385*(L_{pAF\_ShortLeq\_01} - L_{pAF\_ShortLeq\_10}) - 3.5256369 \quad (1)$$

Table I shows an example of summands (resulting from median values of the current study), corresponding units and factors for calculating an exposure-response curve.

$$AWP_{FT} = \frac{e^{A_{FT}}}{1+e^{A_{FT}}} *100 - AWP_{SP} \quad (2)$$

AWP_{FT} – Awakening probability due to a freight train pass by
AWP_{FT} – spontaneous awakening probability. here: 5.7 %
$L_{pAF,max}$ – maximum sound pressure level, fast and A-weighted

$L_{pAF\_ShortLeq\_01}$ – L1 - ShortLeq freight train noise
$L_{pAF\_ShortLeq\_10}$ – L10 - ShortLeq freight train noise

$time_{AFA}$ – time after falling asleep
$time_{CST}$ – time in current sleep stage
$time_{FT}$ – passing by duration of freight train

4. Conclusions

This data set on acute physiological effects of nocturnal freight train noise on sleep is well qualified for the development of a night protection concept that limits the strongest physiological response of residents to nocturnal railway noise, the awakening reaction. Thus, also presumed following adverse health effects after long-term exposure can be avoided with this approach. A protection concept for ensuring a restorative sleep of traffic residents has to include both, the limitation of negative physiological as well as negative psychological reactions to noise. Psychological reactions on noise are often related to stress reactions that may lead to adverse health effects after a long-term noise exposure.

5. Acknowledgement

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Maximum-level as an additional criterion for the assessment of railway noise at night: Definition of sleep quality and derivation of a protection criterion based on reported sleep disturbances for standards and regulations

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Summary

In German regulations on railway noise the average sound level L_{pAeq} for day and night-time is the standard rating level to assess the railway noise impact. On behalf of the Hessian Environmental Department an expert report was prepared including re-analyses of existing data on noise effects on health and case studies in order to develop a suggestion for the implementation of a maximum sound level criterion for the impact assessment of railway noise at night-time.

In this contribution criteria of sleep quality and the impact of noise on sleep at night-time are discussed and physiologically measured indicators as well as indicators assessed in socio-acoustical surveys are presented with which an evaluation of maximum sound level criteria for the impact assessment of nocturnal railway noise has been done. Furthermore, in this contribution results on the relationship between reported sleep disturbances, average sound level at night-time, highest maximum sound level of all train types and number of trains are presented. For this, survey data on the effects of railway noise in the Rhine-Main Region in Germany assessed within the NORAH study on Noise-Related Annoyance, Cognition, and Health have been re-analysed.

In a second Euronoise contribution presented by Müller et al. exposure-response relations of railway noise-induced additional awakenings, the physiological criterion, will be shown. In a third contribution, Möhler et al. present the acoustical sound indicators for describing the maximum sound exposure and suggest a combined protection concept for residents affected by nocturnal railway noise based on maximum sound level criteria.

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1. Introduction

The average sound level L_{pAeq} for day and night-time is the standard rating level in German regulations on railway noise in order to assess the railway noise impact. However, several studies on the impact of transportation noise on sleep have shown the importance of a maximum sound pressure level criterion and the number of noise events as metrics of exposure in exposure-response analysis on noise-related sleep disturbances. This is true for additional, noise-induced awakenings as measured physiologically (polysomnographically) [1] referred to nocturnal aircraft and railway noise as well as for reported sleep disturbances, e.g. due to nocturnal aircraft noise [2].

In this study, existing data on the impact of railway noise at night-time were re-analysed in order to develop a suggestion for the implementation of maximum sound level criteria in German noise regulations for the impact assessment of nocturnal railway noise.

The results are presented in this and two other conference papers (see [3]-[4]). In this contribution it is described how sleep quality can be defined and what indicators of the impact of noise on sleep exist that can be used as impact criteria for the noise effect assessment in regulations. Then, results of a re-analysis of data of the NORAH study on the relationship between reported sleep disturbances due to railway noise, average continuous sound pressure level at night-time, highest maximum sound level of all train types and number of trains are presented.

Sleep is an active and complex process in which a variety of physiological processes take place (e.g. protein biosynthesis, excretion of specific hormones, or the consolidation of memory contents), which serve in the broadest sense of recovery and thus the preparation for the next waking phase Undisturbed sleep of sufficient duration is essential for maintaining psychomotor performance and health (see e.g. [5])

This definition shows that regardless of the exact structure of sleep, it is overall health relevant. Good sleep health [6] is characterized by (1) subjective satisfaction [with sleep], (2) adequate time period, (3) adequate duration (about 7 - 9 hours for a healthy adult according to a consensus American recommendation of the Academy of Sleep Medicine and Sleep Research Society [7]), (3) high efficiency and (4) sustained wakefulness / attention during waking hours. If sleep is impaired with regard to these sleep parameters, further adverse health effects cannot be ruled out.

It follows that both the subjectively experienced disturbance of sleep by noise is an indicator of health impairment, as well as physiological variables indicating that the course of sleep is altered by noise (here: railway noise) so that an impairment of the physical, mental and social well-being has to be expected resp. cannot be excluded.

Porter et al. [8] present a simplified model describing the effects of nocturnal noise in four stages:

(1) acute reactions involving an immediate, direct disturbance by a sound event;
(2) noise effects over a whole night period representing an aggregation of acute reactions within one night;
(3) after-effects at the following day resulting from the noise effects of (1) and (2);
(4) chronic effects that can occur as long-term consequences of (1) to (3).

Physiological and psychological impact criteria were selected for the analysis of the identification of suitable acoustic load characteristics for the assessment of nocturnal railway noise. These criteria are based both on the acute event (physiological effect) and as well on the evaluation of the noise-related disturbance over several nights (psychological effect).

As a psychological impact criterion, the percentage of highly sleep-disturbed persons (% HSD) was chosen. The selected physiological effect criterion is the strongest physiological effect of nocturnal railway noise on sleep, the awakening reaction, for which an ecologically valid exposure-response curve for the probability of awakening due to a railway noise event was derived.

2 Methodology

The %HSD criterion has long been established internationally in procedures for assessing the impact of noise on the population. In a recent review of the effects of nocturnal environmental noise on sleep as part of the WHO World Health Organization's WHO Environmental Noise Guidelines update [9], the %HSD criterion has been revisited. Furthermore, the %HSD criterion is used, for example, in the European Environmental Noise Directive 2002/49 / EC [10].

In the present paper, sensitivity analyses are used to calculate three types of exposure-response models for %HSD. The disturbance data were obtained in surveys on railway noise from the NORAH study, conducted in 2012 in the Rhine-Main area [11]. This study allows, among other things, to investigate the combination of psychological effects with different acoustic characteristics of railway noise burden. The railway noise as investigated in the NORAH study include a broad range of various types of trains with different traffic volumes as it is common in the current German railway network. For the re-analysis of data from the NORAH study, the reported sleep disturbances due to railway noise during the time of falling asleep, during sleep, early in the morning (while waking-up), and overall (mean score from the three individual ratings on sleep disturbance) in the past 12 months were considered. The sleep disturbance assessments were each based on the ICBEN recommendations on the assessment of noise annoyance [12] as specified in ISO/TS 15666 [13], using a five-step response scale from "(1) not ..." to "(5) extremely disturbed". Subjects with the indication of "(4) very" and "(5) extremely" disturbed during sleep were classified as "highly sleep disturbed" (HSD). Depending on the impact variables, data from 2,062 to 2,072 people were included in the analysis.

The three model types represent logistic regressions of %HSD at falling asleep, during night sleep, when waking-up as well as in total. They all refer to the following acoustic characteristics:

a) Equivalent average continuous sound pressure level during the night $L_{p\mathrm{Aeq,22\text{-}06h}}$;
b) Highest maximum sound pressure level $L_{p\mathrm{AF,max}}$ for all types of trains;
c) Combination of maximum sound pressure level and nocturnal number of trains (10 pm to 6 am) in the radius of 250 m.

For all models, the additional factors (co-determinants) “survey mode” (telephone vs. online), “nocturnal air traffic noise level $L_{p\mathrm{Aeq,\ 22\text{-}06h}}$” and “nocturnal road traffic noise level $L_{p\mathrm{Aeq,22\text{-}06h}}$” were included. Logistic regression models were evaluated for model fit using the Akaike Information Criterion (AIC). This is a measure for the goodness of fit of a regression model. On the one hand, the AIC rewards the goodness of fit by means of the likelihood function and on the other hand "penalises" the addition of further predictors [14]. Thus, this penalty prevents an "overfitting", because increasing the number of model parameters usually improves the quality of fit. Lower AIC values mean better model fit.

3. Results

The model calculations show that the proportion of high sleep-disturbed persons due to railway noise (%HSD) rises both with increasing nocturnal continuous equivalent sound pressure level and with the highest maximum level across all types of trains and the number of trains. It emerges from the exposure-response models examined that the continuous average equivalent sound pressure level alone is not necessarily the noise level with the best fit as a measure for the prediction of the %HSD proportion. With respect to all psychological sleep disturbance variables, either the highest maximum level across all types of train alone or in combination with the number of trains better reflects the %HSD rate (see Table 1).

In particular, the exposure-response relationships to sleep disturbance as a whole (total score) are relevant for the consideration of the maximum sound pressure level criterion for nocturnal railway noise. Figure 1 shows the exposure-response curves for the %HSD portion of railway noise of sleep-disturbed persons (total score) related to the nocturnal continuous average sound pressure level (model A) and the highest maximum level across all types of trains (model B).

Table I. Model fit (AIC) of logistic regressions of %HSD to metrics of sound exposure.

Model	A	B	C
	$L_{p\text{Aeq},22\text{-}06\text{h}}$	$L_{p\text{AF,max}}$	$L_{p\text{AF,max}}$ + number of trains
%HSD – falling asleep	1409.63	1397.53	1402.05
%HSD – during night	1265.97	1262.59	1272.95
%HSD – awaken on early morning	1271.00	1269.15	1267.23
%HSD – Sleep disturbance (total score)	1023.97	1020.63	1023.14

AIC = Akaike Information Criterion (lower values = better model fit)

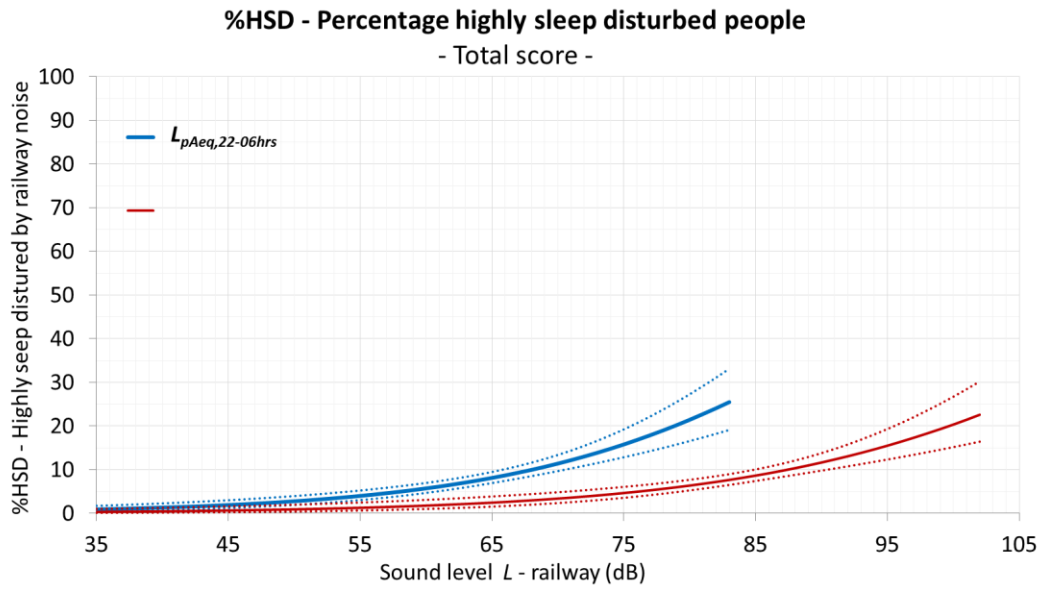

Figure 1: Proportion of highly sleep disturbed persons due to rail traffic noise (% HSD) as a function of nocturnal railway noise level $L_{p\text{Aeq},22\text{-}06\text{h}}$ (blue) or maximum level $L_{p\text{AF, max}}$ (red)

4. Conclusions

The implementation of a maximum level criterion for the night time period seems necessary because the %HSD level differs considerably in terms of the average sound pressure level and with regard to the maximum level in their absolute levels. At levels of $L_{p\text{Aeq},22\text{-}06\text{h}}$ higher than about 55 dB the exposure-response function for %HSD related to the average sound level underestimates the percentage of highly sleep disturbed people when the difference between $L_{p\text{AF,max}}$ and the $L_{p\text{Aeq},22\text{-}06\text{h}}$ exceeds 17 to 20 dB.

The implementation of a maximum level criterion or a physiological effect criterion related to the maximum level is additionally recommended while maintaining the average continuous sound pressure level.

This is also supported by the fact that, depending on the observed phase of nocturnal sleep (when falling asleep, during sleep time or time of waking-up), only the maximum level or the combination of maximum level and number of trains has a better model fit for predicting the proportion of sleep-disturbed persons. Since the average sound pressure level contains both information (noise level and number of events), this indicates that the average continuous sound pressure level should be maintained plus a supplement by a maximum level or performance criterion based thereon.

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Maximum sound pressure level as an additional criterion for the assessment of railway noise at night: Acoustic criteria for the maximum-level in regulations

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Summary

In an interdisciplinary study it was examined whether the effects of rail noise on sleep were adequately assessed by the equivalent continuous sound pressure level. A reanalysis of existing studies on the psychological and physiological effects of nocturnal railway noise lead to the result, that in addition to the equivalent continuous sound pressure level, the introduction of 2 maximum-level criteria is required. By the determination of a maximum difference between the maximum sound pressure level and the equivalent continuous sound pressure level of 17 dB the psychological effects are considered; by introducing a maximum number of reasonable awakening reactions, the physiological effects are adequately considered. In order to implement these criteria, a calculation method for the evaluation of the maximum sound pressure level on the basis of Schall03 as well as a method for the further assessment were developed.

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1. Introduction

In order to implement the results of the psychological and physiological examinations into directives and regulations (see Müller et al. 2018 [1], Schreckenberg et al. 2018 [2]), a procedure is required for the computational determination of the acoustic exposure of those affected persons. The characteristic variables for the event-related effect of passing trains are based on different maximum-level definitions, which differ according to the level of detail of the forecast and the predictability.
This contribution is part of a study commissioned by the Hessian Ministry of Environment [3]

2. Calculation method for maximum noise level

The calculation of the maximum level for railway noise is currently not regulated in Germany. Therefore, a calculation method for the maximum level was derived from the calculation method, which is introduced in the German noise regulations for railway noise "Schall03" [4] by using the method of NORD 2000 [5] as a limited linear sound source (corresponding to the train length). The line sound source - corresponding to the length of a train - is iteratively moved along the track and a propagation calculation to the immission point is carried out at each iteration step.

The propagation calculation follows the rules according to Schall03; which refers to ISO 9613-2 [6]. From these partial sources at each iteration step the immission level is calculated at the immission points. This way the time pattern of sound level is simulated, comparable with sound measurement following DIN EN ISO 3095 [7]. The calculation method can be integrated into the existing Schall03 calculation procedure.

The calculation values do not take into account that individual vehicles in a train may have different emissions (see fig.1), such as defective wheel sets (flats, polygons) or particularly loud bodies of goods wagons. In order to be able to map these temporally short level maxima in the forecast, individual short-term events are taken into account by a distance-dependent level addition, in addition to the maximum level determined by the emitting line source. The basis is the measurement data from the

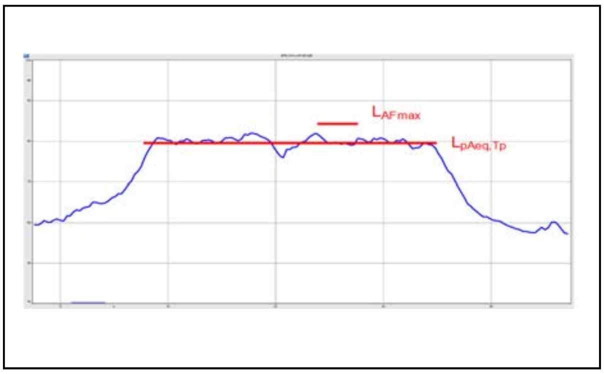

Figure 1. Definition of Maximum level according to DIN EN ISO 3095

DLR study [3]. the relationships are shown in Figure 2:

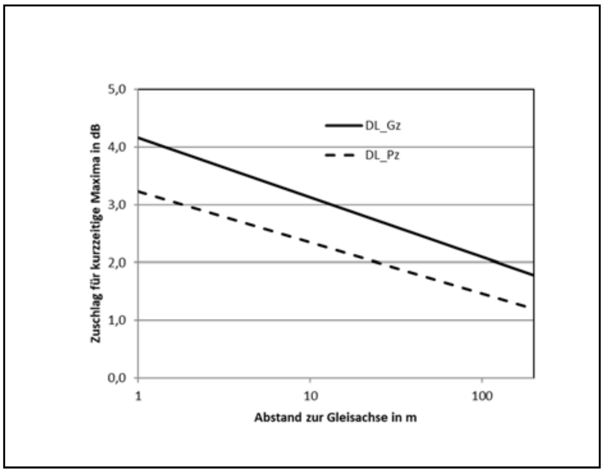

Figure 2. Relationship between extra charge for individual events and distance

The range of the extra charge decreases with the distance from about 3 dB(A) in the immediate area to 0 dB(A) at a distance of about 150 m.

3. Acoustic description of sleep interference on the basis of psychological and physiological surveys

The reanalysis of the NORAH study (see [2]) has shown that the percentage of persons who are highly disturbed at sleep differs significantly, depending on whether the maximum level or the averaging level is used as the criterion. The exposure – response relationship for sleep disorders shown in

Figure 3 results in the fact that an immission threshold of 49 dB (A) based on immission targets of traffic noise in Germany during nighttime leads to an amount of2.6% of indviduals who are particularly disturbed by sleep.

The same number of highly disturbed sleepers results in a maximum level outside of about 66 dB, as shown in Figure 3.

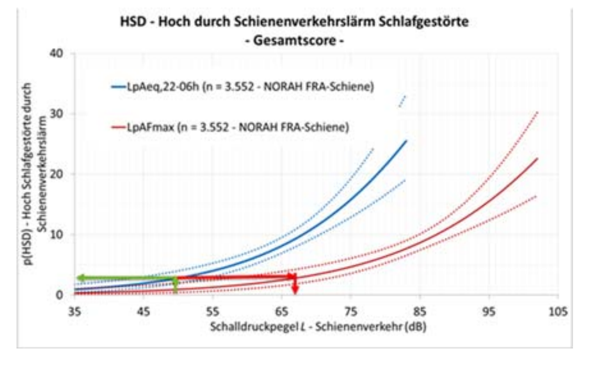

Figure 3. % Highly sleep disturped vs. L_{Aeq} and L_{Amax}

The result of the physiological part of the study was the relation between the probability of awakening and the maximum sound level inside of bedrooms (see[1]). In order to quantify the awakenings in a similar way as the psychological effects, the awakenings were related to the maximum sound level outside the room, the persons were sleeping in. Furthermore the number of awakenings had to be quantified for the night time, dependent on the total number of train pass-byes.

For the calculation of the number of awakenings (AWR) the following steps are necessary:

1.) Calculation of the maximum sound level by Schall03 for every single train
2.) Correction of individual events
3.) Correction of inside / outside
4.) Distribution of the maximum level with a standard deviation of 3 dB
5.) Calculation of the individual frequency of awakening dependent on single trains
6.) Accumulation of awakenings during night time between 10.00 pm and 06:00 am

Limits for the number of awakenings (AWR) at nighttime have not been introduced in Germany yet.

4. Case studies for the description of sleep interference on the basis of psychological and physiological surveys

The effects of %HSD and AWR as a supplementary assessment criteria in a possible regulation are shown in two very different case studies. Here a situation with a low traffic volume load with about 20 train pass-byes at night, of which 6 were freight trains, and a situation with a high volume of traffic with about 100 pass–byes with about 70 freight trains was selected. The calculations were carried out for immission sites in the vicinity of the tracks at a distance of 30 to 100 m from the track axis. The results are listed in following table 1:

Table 1. Results of the case studies without noise protection

Pass byes	$L_{r,N}$	L_{Amax}	L_{Amax}-$L_{r,N}$	Delta %HSD*	AWR
20 trains/night	60	87	27	4	1,2
100 trains/night	60	79	19	0,2	5,7

* %HSD L_{eq} -L_{Amax}

- The difference of %HSD between L_{Aeq} and L_{Amax} is particularly large in the case of low traffic volume
- The corresponding difference between those in the case of high traffic volume is small
- The number of train-induced awakening reactions (AWR) in the case of low traffic volume is only 1 additional AWR, whereas in the case of high traffic volume there are 6 additional AWR

In the case of noise protection for the same traffic situations the results are shown in following table 2:

Table 2. Results case studies with noise protection

Pass byes	$L_{r,N}$	L_{Amax}	L_{Amax}-$L_{r,N}$	Delta %HSD*	AWR
20 trains/night	48	74	26	1,9	0,8
100 trains/night	49	68	19	0,4	3,8

* %HSD L_{eq} -L_{Amax}

With noise barriers in both cases the L_{Aeq} as well as the L_{Amax} can be reduced to about 10 to 13 dB. As a result of the measures regarding the case of low traffic volume the %HSD is reduced by about 60% from 4 to 1.9, whereas the number AWR is reduced by about 30% from 1.2 to 0.8.
In the case of high traffic volume with noise barriers a significant reduction of AWR from 5.7 to 3.8 can be achieved whereas the reduction of %HSD is marginal.

5. Additional noise limits for maximum noise level

The reanalysis of the NORAH study has shown that there is a clear difference of %HSD depending on whether the L_{Aeq} or the L_{Amax} is used as a criterion. At the noise limit of 49 dB(A) in Germany the difference between the two levels is 17 dB. In order to avoid a higher %HSD based on L_{Amax} it is required that the maximum level does not exceed the averaging level by more than 17 dB. For practical application we propose a value of 15 dB(A) as a maximum sound level criteria. In addition the number of awakenings should be limited on 3 awakenings. Both assessment criteria are to be applied in addition to the regular noise limits related to the L_{Aeq}.
In practical application, these additional criteria lead to improved noise protection measures in the immediate vicinity of railway lines.

6. Conclusions

The reanalysis of existing studies on the psychological and physiological effects of nocturnal railway noise leads to the result, that in addition to the equivalent continuous sound pressure level, the introduction of 2 maximum-level criteria is s required:

The difference between L_{Amax} and L_{Aeq} is to be limited to 15 dB(A) and the maximal number of awakenings should not exceed 3 AWR.

In further steps, the calculation method for the L_{Amax} is to implement in standard calculation methods (Schall03, CNOSSOS-EU). Further tasks are finding a method to determine the AWR and discussing suitable AWR limits

Acknowledgement

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