Sound Exposure Levels from Trains and Sleep Disturbance

J. JABBEN[1]; C. POTMA[2]

[1,2] National Institute for Public Health and Environment (RIVM), The Netherlands

ABSTRACT

Train passages during the night can seriously affect the sleep quality in nearby dwellings. Ongoing research aims to improve our understanding of how environmental noise, in connection with human physiology, causes sleep disturbance. A widely used approach to estimate noise effects on sleep quality is to make use of dose-response relations with L_{night} as a predictor for the percentage of disturbed people. The underlying mechanisms that govern sleep disturbance by noise events are still not fully understood and predictions can deviate considerably from surveys. An alternative approach is to assess the probability of sleep disturbance of each individual event and deduce the overall sleep quality from all individual events during the night. In this paper, both methods are compared for railway noise, using RIVM monitoring results of sound exposure levels from trains over 2013. The paper discusses how a better understanding of sleep disturbance by individual noise events, may help to improve or refine dose-response relations that are based on long time average noise levels.

Keywords: Noise, Train, Sound Exposure, Sleep, Disturbance
I-INCE Classification of Subjects Number(s): 52.4, 63.4, 66.1, 68.3, 72.1

1. INTRODUCTION

Noise events from trains, airplanes and trucks during the night can cause awakenings or hamper falling into sleep thereby interfering with recuperation from daily activities by healthy natural sleep. Therefore, in many countries limits for maximum allowable noise levels are prescribed.

The underlying mechanisms that govern sleep disturbance by noise events are still moderately understood. Different approaches exist for the prediction of sleep disturbance from noise. One can apply a dose-response function that uses L_{night} as a predictor for estimating the percentage of the population that perceives (severe) sleep disturbance. Often Miedema's dose-response relations[1] for motorways, railways and airports are used, but also other dose-response relations are used. An alternative method, which has gained more interest in recent years, consists of assessing each single noise event with regard to the probability of awakening and use the results to evaluate the overall sleep quality during the night.

This paper compares the prediction of sleep disturbance from trains by both methods when long time measurements are used that yield both L_{night} and SEL-values of individual train passages. The measurements are available from RIVM's noise monitoring network which has been extended considerably in 2012 and 2013 at sites along Dutch railways and motorways[2].

2. MONITORING SOUND EXPOSURE LEVELS FROM TRAINS

In 2012, the Dutch noise act was provided with new regulations for motorways and railways. Future noise levels (L_{den} in dB(A)) caused by motorways and railways have to remain below limits at (fictitious) reference points. The reference points are located at 50 m from the outer lanes or railway tracks and spaced 100 m apart. The limits (in the new Dutch legislation called 'noise ceilings') apply to 60.000 reference points for both motorways and railways.

[1] jan.jabben@rivm.nl
[2] charlos.potma@rivm.nl

When the new legislation was proposed, the Dutch Parliament demanded that on a sample of the reference points the calculated noise levels will be validated by independent measurements and the Ministry of Infrastructure and Environment has commissioned this task to RIVM. To this aim, the noise-monitoring network of RIVM was extended in 2012 and 2013 and now comprises 52 measurement sites. The network consists of both class-1 and class-2 microphones[3]. All the sites are in permanent operation and noise levels are monitored continuously. Figure 1 shows the locations of the measurement sites along railways in December 2013.

Figure 1 – Dutch Railway monitoring sites in 2013 with class-1(red) and class-2(blue) microphones

During monitoring, Sound Exposure Levels (*SEL*) of each train passage are registered. In order to avoid the influence of noise events that are not caused by trains, use is made of the following criteria:

- *SEL* registration starts only above a threshold level and stops below that level
- L_p levels during passage should be 10 dB higher than the background level
- Event duration is bound between set minimum and maximum duration.

An example of the measurements is shown in Figure 2, obtained at site nr 2 at Hulten. Each train passage is clearly visibly in the time series and continuous monitoring allows one to determine both the exposure levels and the amount into which they occur. The information is not merely limited to an incidental one-day or one-night measurement, but offers a complete picture of exposure and occurrences throughout the year.

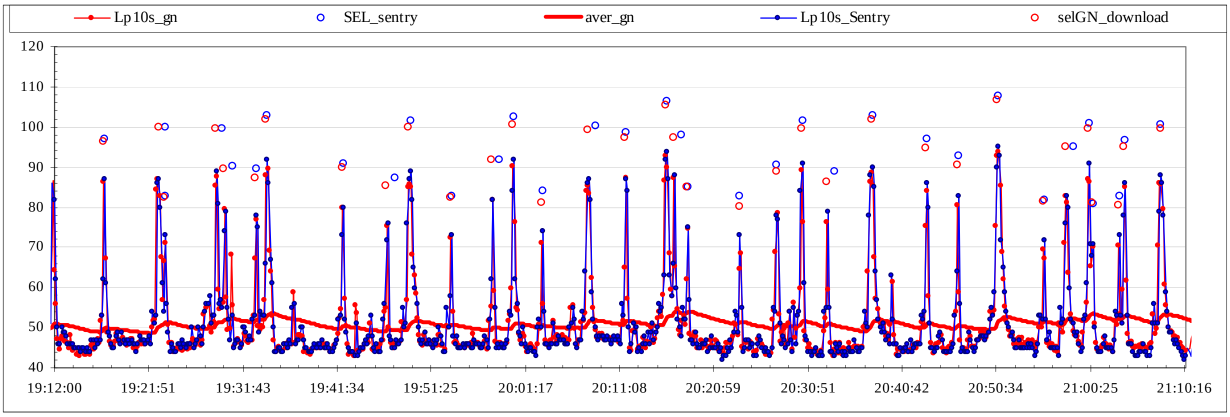


Figure 2 – Example of measured time series and *SEL* values corresponding to the train passages at Hulten

As compared with calculated noise levels using models, time series obtained by continuous measurements offer much more information and detail that can be highly relevant for dose-response studies. If reliable and sufficient input data (number of trains per category, speed, rail roughness etc) are available, models can give a good estimation of average L_{Aeq} levels during day, evening or night. However, in practice it is often difficult to get good and complete traffic data. Furthermore, calculation models for railway noise usually attribute the same noise emissions for all trains that belong to a certain train category, while emission levels that occur in practice can show a large variety within these categories.

3. TRAIN NOISE AND SLEEP DISTURBANCE

3.1 Awakening induced by single events

Sleep disturbance by noise is a complex physiological process. It is usually difficult to predict if, and to what extend a certain noise event will affect or interrupt a person's sleep. Nevertheless, there is a vast amount of research and literature into the subject, that proposes *SEL*-models for predicting the chance of awakening by a single noise event. An excellent research overview can be found in McGuire and Davies[4]. Their inventory is summarized in Figure 3. The relations in Figure 3 are proposed for predicting awakenings caused by aircraft noise. In this study we assumed that these single event relations, to first approximation, can also be applied to predict awakenings from train noise. In a recent study of Elmenhorst et al[5], 'nocturnal freight train noise exposure in Germany was associated with increased awakening probabilities exceeding those for aircraft noise and contrasting the findings of many annoyance surveys and annoyance ratings'.

Although the probability curves in Figure 3 show considerable differences, particularly the model from Andersen and Miller above *SEL*-levels of 100 dB(A), the overall agreement is not too bad. The picture that emerges is that when noise events cause indoor *SEL*-levels above 60 dB(A), sleep disturbances or interruptions are likely to occur. This still leaves considerable degrees of freedom regarding the actual average noise level L_{Aeq} during the event and its duration T, which are related according to $SEL = L_{Aeq} + 10\log(T)$. A *SEL*-level of 80 dB(A) is equivalent to by an L_{Aeq} of 70 dB(A) over 10 seconds or an L_{Aeq} of 60 dB(A) over 100 seconds.

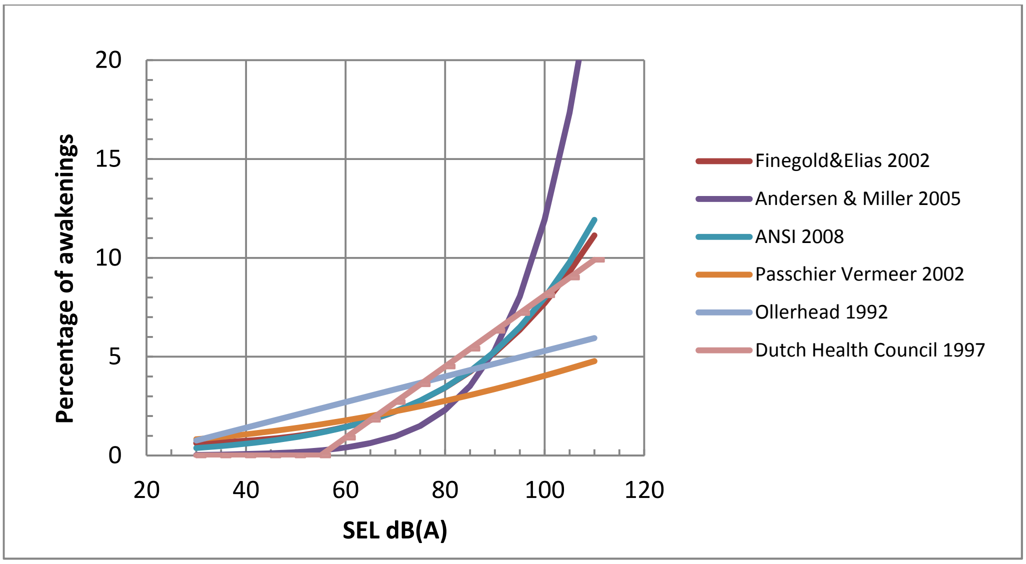


Figure 3 – Probability of behavioral awakenings depending on (indoor) *SEL*-levels, as reported by McGuire and Davies[4]

3.2 Awakening induced by multiple events

The majority of the curves shown in Figure 3 predict a 2 - 4% chance of awakening from a single noise event causing an indoor *SEL*-level of 80 dB(A). In the following, we take the ANSI 2008- curve[6] as a reasonable average to discuss a technique for assessing the number of awakenings when multiple train events occur during the night.

To predict the overall sleep-quality during the night, given a set of *SEL*-measurements, it is straightforward to use single event probabilities to determine the overall chance that a person's sleep will remain undisturbed i.e. that no awakenings will occur[6]. This probability can be determined according to:

$$P_0 = \prod_{i=1}^{N} \left(1 - P_{w,i}\right) \tag{1}$$

, in which P_0 is the chance that sleep is undisturbed, $P_{w,i}$ the chance that event nr i causes an awakening and the product extends over all noise events during the night. The probability that a person wakes up during the night at least one time (P_{1+}) follows from $P_{1+} = 1\text{-}P_0$.

Eq. (1) also involves the probability when just one event during the night will disturb or interrupt sleep. These nights will probably attribute less to being severely sleep disturbed then nights when 2, 3 or more awakenings occur. A more thorough approach is to also consider the chances P_1, P_2 ... P_m of awakening $1,2\ldots m$ times during the night. Such an approach is possible, although the calculation is more elaborate and requires the use of combinatorics. Assuming that the events are sufficiently separated in time and cause independent chances of awakening, the probability of m awakenings by N train events is given by:

$$P_m = P_0 \sum_{i=1}^{N-m+1} \sum_{j=i+1}^{N-m+1} \cdots \sum_{s=r+1}^{N} \frac{P_{w,j}}{(1-P_{w,j})} \cdots \frac{P_{w,s}}{(1-P_{w,s})} \tag{2}$$

The probability of awakening m or more times follows from $P_{m+} = P_m + P_{m+1} + P_{m+2} + \ldots$ and allows for more gradation in the evaluation of sleep quality as compared to considering merely P_{1+}. This is further illustrated in chapter 4.

4. APPLICATION AND RESULTS

Eq. (1) and (2) were applied to a time series measured at Hulten in 2013 (site nr 2). The day- to-day probabilities of awakenings were calculated according to Eq. (2), using the single event probability (P_w) as given by the ANSI-2008 standard[6]. The results are shown in Figure 4. The average L_{night} over the whole measuring period, February - December 2013, is 68 dB(A). Closed proper windows with an insulation of 30 dB were assumed, yielding an average indoor level of 38 dB(A). The minima in L_{night} coincide with nights from Saturday on Sunday. P_m is the calculated probability that sleep disturbance or disruption occurs m times, $1\text{-}P_0$ is the probability that this occurs at least one time. Probabilities P_1 to P_3 attain significant values. The probabilities P_4 and P_5 are practically zero, regardless of L_{night}, and so here $P_1+P_2+P_3 \approx 1-P_0$.

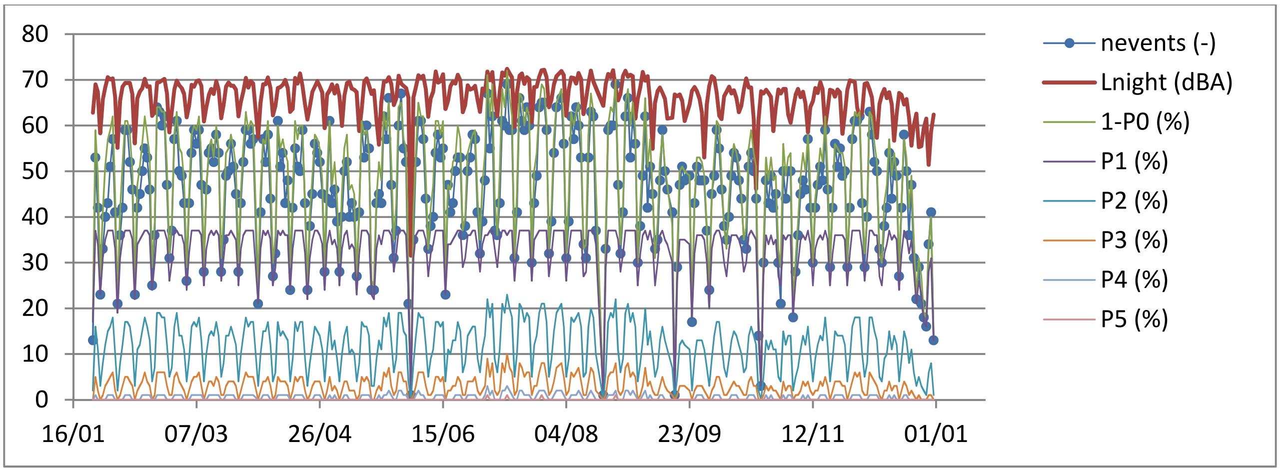
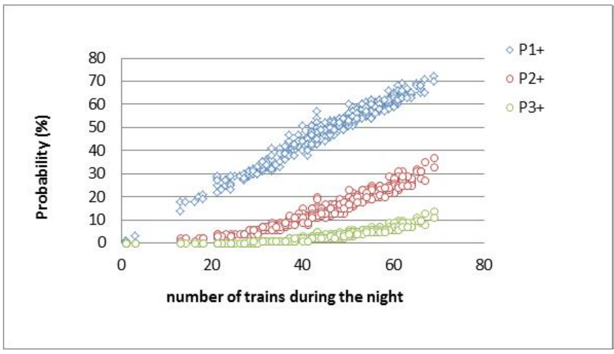


Figure 4 – L_{night} (dB(A)) and number of trains measured during February - December 2013 at site nr 2.

In Figure 5a The probabilities of awakening at least one, two and three times (P_{1+}, P_{2+}, P_3) during the night are plotted against the number of trains passages. Each dot represents 1 night, 336 nights in total. As the figure shows, P_{1+}, P_{2+} and P_{3+} show good correlation with the number of trains during the night. P_{1+} starts to increase linearly immediately, while for P_{2+} and P_{3+} threshold values (N_0) of around 20 and 40 trains seem to apply. It is interesting to see that the probabilities of being awoken at least two or three times are considerably lower than being awoken at least one time. Figure 5b shows the probabilities if an insulation of 20 dB(A) is assumed.



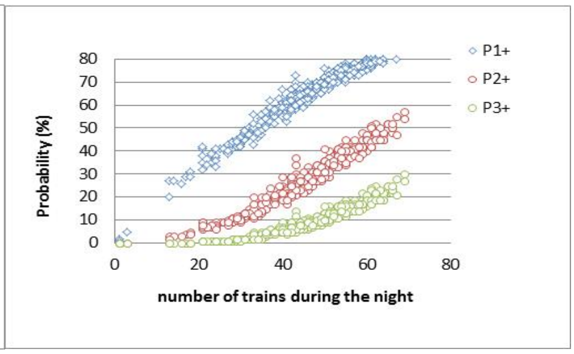


Figure 5a – (left) Probability of awakening at least 1, 2 and 3 times plotted versus the number of trains during the night with 30 dB insulation, indoor L_{night} 38 dB(A).
Figure 5b – (right) Probabilities with 20 dB(A) insulation and indoor L_{night} 48 dB(A)

Figure 6 shows the probabilities P_{1+}, P_{2+} and P_{3+} versus L_{night} as calculated over all train events during the night, at 30 dB insulation. The probabilities of awakening show correlation with L_{night}, although with considerable more deviation. In Figure 6, also the dose response relations as found by Kim[7] and Miedema[1] are shown.

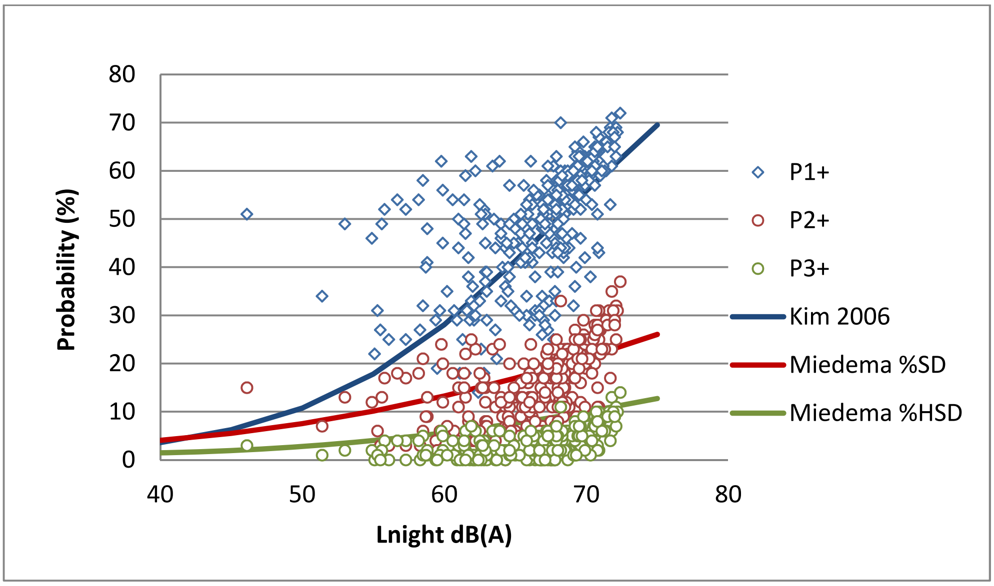


Figure 6 – Probability of awakening at least 1, 2 and 3 times plotted versus L_{night} (outdoor). Also shown are dose-response relations according to Kim and Miedema

5. DISCUSSION

What can we conclude from these results? An interesting observation is that if we use the ANSI-probability curve to predict awakenings from single noise events, the probabilities P_{1+}, P_{2+}, P_{3+} of awakening at least 1, 2 and 3 times seem to show better correlation with the *number* of trains as compared with the average noise level L_{night}. We see a considerable number of nights with a high probability of awakening despite a relatively low average outdoor level L_{night}, particularly for P_{1+}.

As for the relation between P_{1+}, P_{2+}, P_{3+} and the *number* of noise events, in general this relation will depend on the average indoor level, i.e Figure 5a and 5b only hold for indoor levels of 38 and 48 dB(A). At higher average indoor levels, the slope increases and the threshold level (N_0) decreases. So a more general relation probably would be of the form $P_{n+} = a_n(L)+b_n(L)\cdot(Nevents-N_{0,n}(L))$. Sofar this relation has not been explored further.

An interesting question is how the probability of being awoken at least 1, 2 etc times relates to the percentage of exposed people that feels being 'highly sleep-disturbed' (*%HSD*). The results in Figure 6 suggest that the *%HSD* in Miedema's dose response relation corresponds to being awoken at least 3 times P_{3+}, the percentage of sleep-disturbed (*%SD*) to P_{2+} and Kim's dose-response function to P_{1+}. However, a full exploration of this relation would require further research that should be supported with real physiological data. A further note of caution is that the probabilities presented in this paper are theoretical by nature. For example P_4 and P_5 were found to be practically zero, but after being awoken three times, there is a chance that a person may not be able to fall into sleep again.

Although the current dose-response relations based on L_{night} are useful and can give a first estimate of the way that sleep is affected by railway traffic, there is still a need for refinement and a better understanding of the way that event-like noise exposure accumulates to the overall experienced sleep quality. This not only goes for noise events, but also applies to the effect of train induced ground vibrations.

The latter topic is drawing more attention in the Netherlands (e.g. van Kamp[8]) because it causes considerable problems, particularly along lines with freight trains during the night. Better insight into sleep effects and consequences for health is needed in order to provide policymakers with adequate limits that may enforce protective measures. Also in other countries sleep disturbance from rail vibration events are a concern and initiating new research[9,10] into suitable dose-response relations. The technique outlined in this paper for deriving P_{1+}, P_{2+} etc from single noise events may also be applicable for vibration events, if the probability of awakening from a single vibration event can be determined.

Apart from the type of dose-response relation that is applied, long-term measurements of noise and/or vibration levels can help to improve these relations. Measurements allow for a relatively accurate determination of each single noise and/or vibration event that occurs during the night, over many weeks or months of exposure. This results in a detailed and extensive profile of the exposure, which is difficult to obtain by mere calculation.

6. CONCLUSIONS

- Although the current dose-response relations based on L_{night} are useful en can give a first estimate of the way that sleep can be affected by railway traffic, there is still a need for refinement and a better understanding of the way that event-like noise exposure accumulates to the overall experienced sleep quality. Better insight of the way that noise events and their number affect sleep quality can help to provide policy makers with more effective noise limits.

- If the ANSI-curve is used for the prediction of the chance of being awoken by a single noise event, then the probabilities of being awoken at least 1, 2, ... times show strong correlation with the number of events. The results suggest that prediction of sleep disturbance involves both the average L_{night} level and the number of events.

- The technique outlined in this paper for deriving the probability of awakening at least 1,2.. etc times from single noise events may also be applicable for vibration events if the probability of awakening from a single vibration event can be determined.

- Apart from the dose-response relation that is applied, long-term measurements of noise and/or vibration levels can help to improve these relations. Measurements allow for a relatively accurate determination of each single noise and vibration event that occurs during the night, over many weeks or months of exposure. This results in a detailed and extensive profile of the exposure, which is difficult to obtain by mere calculation.

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