METHOD FOR CALCULATING THE PROBABILITY OF NOISE-INDUCED SLEEP STATE CHANGES FROM INTERMITTENT SOURCES OF TRANSPORTATION NOISE

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Transportation at night is regarded by industry as a commercially important part of operations. However, disturbance of sleep arising from night-time operations is one of the least acceptable aspects of transportation to local communities. Methods for establishing the impact of sleep disturbance based on 8hr night-time equivalent noise levels are available and are widely used in the application of EU and UK noise policy. However, it is important to recognise that disturbance at night is not just about average levels of noise exposure and that the number, frequency and occurrence of noise events and their respective noise levels are as, if not more, important. A number of detailed laboratory and field studies on sleep disturbance as a function of maximum sound level and rise time have been carried out by the German Aerospace Centre in recent years. This paper describes a method for calculating the probability of noise-induced sleep state changes for new or existing transportation schemes using measured polysomnography data. This method considers the evidence of sleep disturbance from transportation noise and outlines how it could be applied to address national or project specific environmental criteria.

Keywords: Sleep disturbance, transportation noise, polysomnography

1. Introduction

The WHO Night Noise Guidelines for Europe [1] cites numerous studies that detail the effects of transport noise on sleep. Studies have shown that noise can effect sleep in terms of immediate effects (e.g. arousal responses, sleep state changes, awakenings, body movements, total wake time, autonomic responses), after-effects (e.g. sleepiness, daytime performance, cognitive function) and long-term effects (e.g. self-reported chronic sleep disturbance).

Sleep disturbance can be quantified either by the number of physiological or behavioral awakenings, or by subjective means. Physiological and behavioral measurements tend to show lower levels of actual disturbance than might be inferred from subjective reports of perceived sleep disturbance – often termed 'self-reported' [2]. Although subjective estimates of sleep quality and quantity can be disproportionate with the number of noise induced awakenings, self-reported sleep disturbance remains the most easily measurable subjective outcome indicator and an important indicator of community response to noise.

Miedema & Vos [3] published the results of an updated meta-analysis of twenty eight datasets from twenty four field studies of self-reported sleep disturbance from transport noise using the outdoor L_{night} noise indicator. The results confirm earlier findings that at the same equivalent night time noise exposure levels, aircraft noise is associated with more self-reported sleep disturbance than road traffic noise, and road traffic noise is associated with more sleep disturbance than railway noise.

Electrophysiologically-measured awakenings (sleep state changes) do not suffer from subjective misjudgments of sleep quality, because the noise and electrophysiological signals are simultaneously measured. Studies by the Institute of Aerospace Medicine at the German Aerospace Center (DLR) on aircraft noise and railway noise [4,5,6] were performed using a random effects logistic regression model to give the probability of noise induced sleep state changes (EEG awakening) with increasing $L_{p,ASmax}$, relative to spontaneous (non-noise related) awakenings (circa 24 awakenings usually occurred even during undisturbed eight hour nights). The results show that noise from freight trains caused significantly more awakenings than noise from passenger trains, the latter inducing less awakenings than aircraft noise.

To assess the effects of nocturnal noise from a new or modified transport infrastructure project the IEMA guidelines [7] recommend that a risk assessment for be undertaken using available dose-response relationships. This can be used help to define project specific criteria to identify the health effects caused by the scheme so that measures can be developed to avoid or reduce the adverse effects and in some situations promote beneficial effects.

2. Polysomnography Measured Sleep Outcomes

Polysomnography, i.e. the simultaneous recording of the electroencephalogram (EEG), the electrooculogram (EOG), the electromyogram (EMG), and other physiological variables remains the 'gold standard' for measuring and evaluating sleep [8]. Changes in brainwave patterns are categorized by arousals, sleep stage changes, or EEG-awakenings. There are four relevant studies that identified the effects of road, rail and aircraft noise on polysomnographically measured sleep. Two studies by the German Aerospace Center (DLR) developed random effects logistic regression models (referred to in this paper as the DLR models) using the same methodologies to give directly comparable probabilities of noise induced sleep state change to awake or S1 for indoor maximum noise levels ($L_{p,ASmax}$) [9].

The aircraft STRAIN study found that both the number and the duration of aircraft noise-induced awakenings played an important role for the evaluation of the effects of aircraft noise on sleep, because the probability of a recalled awakening in the morning increased with the awakening duration. The results of the DLR laboratory study showed that awakening duration increased with the maximum SPL of an aircraft noise event (ANE). Awakenings induced by ANEs with $L_{p,Amax,inside} \leq 65$ dB were relatively short, and were similar in nature to spontaneous awakening. Awakenings induced by ANEs with $L_{p,Amax,inside} \geq 70$ dB were markedly longer than spontaneous awakenings.

The rail DEUFRAKO study found that noise from freight trains caused significantly more awakenings than noise from passenger trains, the latter inducing less awakenings than aircraft noise. The authors suggest that special characteristics of freight train noise, such as sharp and fluctuating sounds and the duration of the noise event may explain some of the difference in probability of awakening [6]. The results showed that railway noise did not lead to prolonged sleep latencies or to impaired sleep efficiency compared to normal population values, and did not show significant relations to the noise exposure received during the night. Subjective sleep latency and subjective problems in falling asleep were not significantly related to noise, nor were subjective depth, calmness, quality and quantity of sleep. Nocturnal railway noise was found to have an effect on psychomotor vigilance.

Important modifying factors within the DLR model for the DEUFRAKO study include the number and duration of train passbys, passby sound rise time, distance to railway, and incidence of perceptible vibration. The probability of noise-induced EEG-awakenings according to the DLR model for railways is a function of both L_{pASmax} and rise time. Rise time is proportional to train speed and inversely proportional to distance from railway. The US Federal Railroad Association

[10] provides some information on measured rise times (onset rates) for a steel wheel train. The data suggests that the rise time experienced by receptors situated 70m or more from the railway for a train travelling at 360km/h is less than 10dB/s and therefore falls within the data range of passenger rail traffic which the DLR model was based on.

In both the STRAIN and DEUFRAKO studies, physiological reactions to road noise were also measured, although the studies were not designed to examine the effects of road noise on sleep [9]. Fig 1 shows the resulting exposure response relationships for observed EEG-awakenings from passenger train, freight train and aircraft noise. These relationships include spontaneous awakenings, therefore the probability for noise-induced awakenings will be lower (observed minus spontaneous).

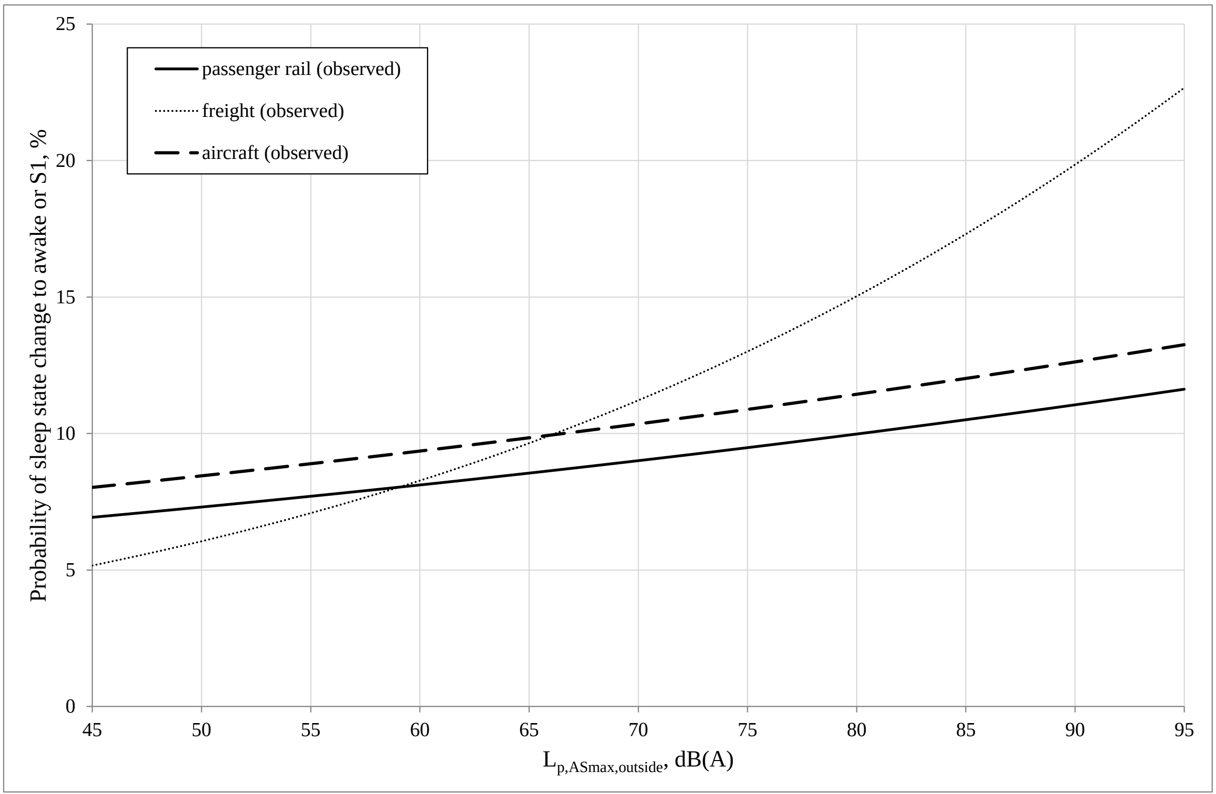

Figure 1: Probability of EEG awakenings due to noise from passenger rail, freight and aircraft traffic, as determined from the DLR studies on sleep disturbance. Curves generated using a random effects multivariate logistic regression model presented by Elmenhorst et al. [6]. Assumptions: level difference between inside to outside = 15dB(A), representative of a partially open window.

2.1 Calculations of noise-induced awakenings

Many studies have shown that sleep state changes are not specific to noise events; they also regularly occur as part of normal every day sleep patterns. Basner et al. [4] report an 8.6% probability of spontaneous awakenings, equivalent to approximately 24 awakenings per night. They used this figure as a baseline against which to derive the probability of noise-induced sleep state changes as a function of the maximum indoor noise level. Fig 2 shows the result of applying this approach to exposure response relationships for observed EEG-awakenings from passenger train, freight train and aircraft noise.

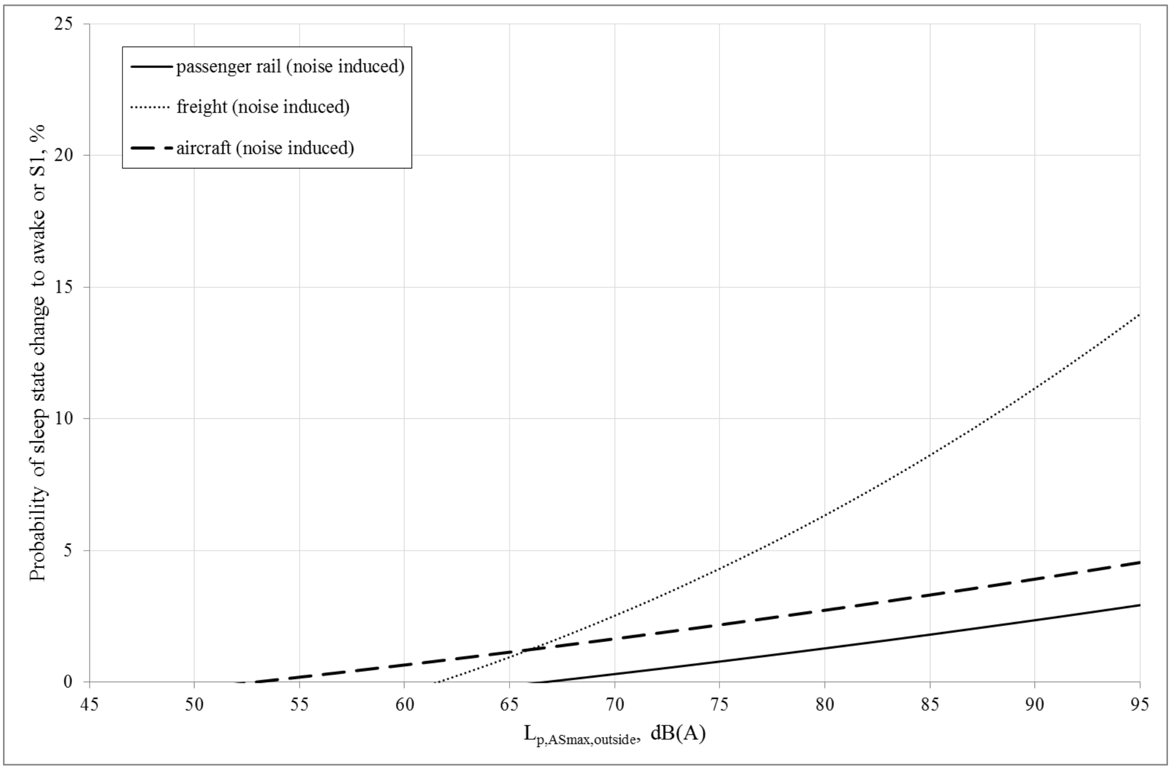

Figure 2: Probability of noise-induced sleep state changes from aircraft, freight and passenger rail traffic as a function of maximum SPL (L_{pASmax}) inside the bedroom. Relationships based on a random effects multivariate logistic regression model developed by DLR. Probability of spontaneous awakenings = 8.6% from Basner et al. [4].

3. Assessments of noise induced sleep disturbance

The long term health consequences of noise induced EEG awakenings are not fully understood. There are some suggestions that humans may be able to adapt to a certain level of noise induced awakening without negative health consequences. On a precautionary basis, it is necessary to consider the effect on sleep resulting from noise-induced EEG awakenings when assessing the likely health effects of transportation noise. In particular, an assessment of the likely change to sleep quality can inform the identification of both adverse and beneficial effects as a result of a new transportation scheme. In order to avoid adverse effects on nonrestorative sleep, resulting from changes in sleep structure, Basner et al. [4] recommended three objectives: (1) On average there should be less than one additional EEG awakening induced by aircraft per night; (2) Awakenings recalled the following morning should be prevented as much as possible; and (3) There should be no impairment to the process of falling asleep again.

3.1 Examples of transport schemes applying the DLR concept

The objectives for the protection against adverse effects of nocturnal aircraft noise have been applied to several airports in Germany including Frankfurt airport, Cologne-Bonn airport and Leipzig/Halle airport. For airports it is possible to illustrate the noise protection zones by predicting the number of noise-induced awakenings for each location around the airport. An example for Frankfurt airport reproduced from Basner [4] is presented in Fig 3. To address the second criterion, it is recognised that there is a greater risk of recalled awakening when the awakening is longer in duration. The laboratory study showed that differences in duration of noise-induced awakenings compared to spontaneous awakenings can occur when maximum sound pressure levels exceed 65 dB in the bedroom [4]. Therefore, to prevent recalled awakenings, the approach taken is to avoid as much as possible nightly maximum sound levels from aircraft noise of 80 dB outside. To address the third criterion, the morning hours and the time period between noise events can be addressed to reduce the risk of preventing the affected population from falling asleep again. The approach taken for the Leipzig/Halle airport is to apply a malus of 1.4dB to maximum sound levels occurring in the second half of the night.

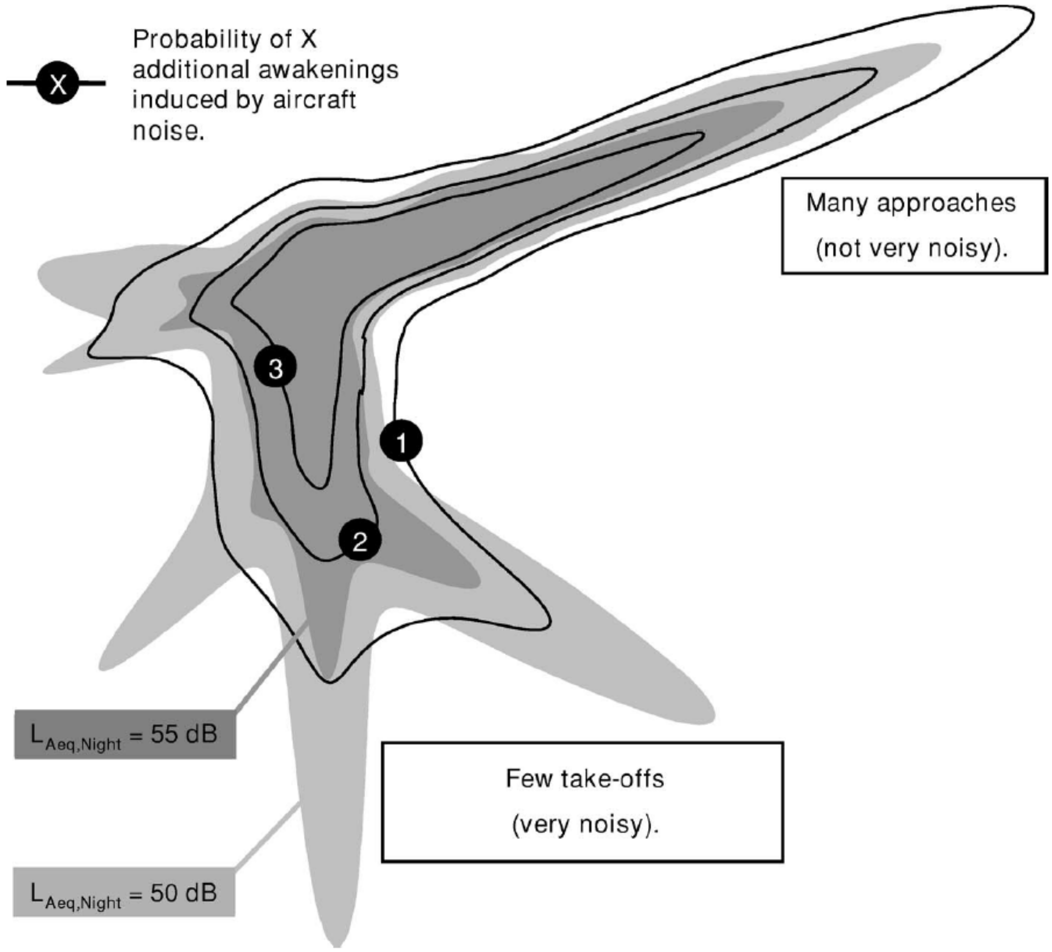

Figure 3: Comparison of LAeq criteria to additional awakenings criteria for Frankfurt airport from Basner [4]. On average one, two or three additional awakenings induced by aircraft noise (black lines), L_{Aeq}=55 dB (drak grey), and L_{Aeq}=50dB (light grey). Calculations are based on 25 000 nocturnal aircraft movements in the busiest six months of the year.

The objectives applied to airports have also been applied for the protection against adverse effects of nocturnal railways noise from the proposed High Speed Two railway in the UK. To ensure the use of integer values for the number of additional awakenings, HS2 predicted the distribution of the numbers of noise induced awakenings over the 365 nights of one year. HS2 selected the busiest section of the HS2 railway between London and the West Midlands where 56 train passby noise events were predicted to occur each night between 22:00 and 07:00 once the second phase of the project is operating. Using the DLR model for passenger railways [6] HS2 predicted 1 additional awakening per night (365 noise-induced awakenings a year) at properties with a partially open window when the outdoor maximum sound level for each event is 80 dB [11]. To avoid adverse effects on nonrestorative sleep, HS2 has committed to offering noise insulation measures for all qualifying residential building exposed to a level of noise equal to or greater than 80 dB (L_{pASmax} at the façade) [12]. This commitment addresses both the first and second criterion. In order to address the third criterion, HS2 made a commitment to Parliament that the operator of the railway would take all reasonable steps to reduce adverse noise effects at night and that this would not exclude considering changes to the number and speed of trains at night.

Table 1: Average number of additional noise-induced EEG-awakenings per year as a factor of maximum sound pressure level calculated using the DLR model for passenger railway noise [6] for HS2 Phase One before opening of Phase Two (36 events) and after opening of Phase Two (56 events) [11]

L_{pASmax} inside bedroom, dB(A)	L_{pASmax} outside property, dB(A)			Number of additional noise-induced EEG-awakenings per year	
	Partially open window	Single-glazed window	Secondary glazing	23:00 – 07:00 (36 events)	22:00 – 07:00 (56 events)
80	95	110	120	402	584
75	90	105	115	329	511
70	85	100	110	219	365
65	80	95	105	183	292
60	75	90	100	110	146
55	70	85	95	37	73
50	65	80	90	0	0
45	60	75	85	0	0

3.2 Future applications of DLR criteria for noise impact assessments

Although the sample sizes of polysomnography studies are small due to the cost and complexity of capturing and analysing data, they allow us to draw conclusions on structural aspects of sleep. When transferring this data to another population, it is possible that the variability in noise sensitivity between subjects in the sleep studies is not representative of the population that the results are transferred to. This limitation to the applicability of the results to other populations can be addressed by applying further preventative measures to address parts of the population that are more sensitive than the subjects in the sleep studies. This includes assumptions regarding the amount of time the sleeper spends in sleep stage S2, that a change to sleep stage S1 is included as an awakening event, the relative proportion of study subjects compared to the general population that consider themselves sensitive to noise, and reasonable worst case predictions of the transportation noise exposure being assessed.

In 2015 the results of the NORAH (Noise-Related Annoyance, cognition and Health) study at Frankfurt Airport were published at the International Conference on Active Noise Abatement. As shown in Fig 4, different relationships for awakening probability and maximum sound pressure levels for aircraft events were sound at Frankfurt and Cologne-Bonn airports [13]. The NORAH study suggests that differences in sleep measured might be explained by differences in the frequency spectrum of the aircraft noise, the number and temporal distribution of aircraft noise events as well as difference in study methods.

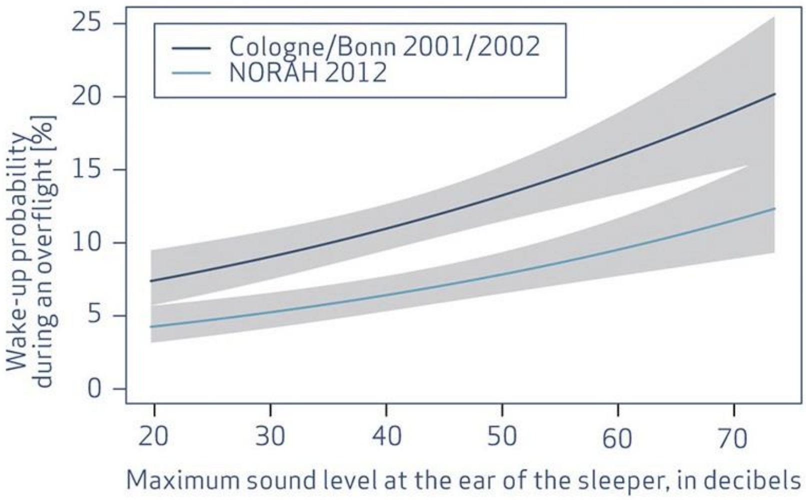

Figure 4: Aircraft noise associated awakening probability at Frankfurt and Cologne-Bonn Airport [13]

For the noise impact assessment of a transport scheme or strategy, the potential adverse or beneficial effects on nonrestorative sleep can be calculated by comparing the number of noise induced awakenings without the scheme to the number of noise induced awakenings with the scheme. In many projects such as HS2 in the UK, baseline measurements are taken to establish the existing noise exposure. Often these baseline measurements document the maximum sound levels from existing transportation noise sources yet they are not directly applied to the quantification of impacts. For each existing nocturnal aircraft, railway or road noise event, awakening probabilities can be calculated using the DLR models [4,6] including a future publication for road noise mentioned by Basner and McGuire [9]. This can then be used to assess the increase or decrease in the probability of noise-induced awakenings resulting from a transport proposal. This provides a method for identifying the noise impacts, effects and mitigation measures for Environmental Impact Assessments (EIA) of situations with combined noise sources. The use of equivalent sound level criteria alone have been shown to be inadequate at predicting additional awakenings from intermittent noise sources [4] and previous attempts have been unsuccessful at validating the annoyance equivalents model using EU exposure response relationships [14]. Since the DLR models addresses many modifying factors and the assumptions can be adjusted to address limitations of applying the study results to the population level, this method can be used to directly address the requirements of the 2014 EIA Directive.

4. Conclusions

The sleep studies performed by the German Aerospace Centre offer models for the predictions of noise-induced awakenings from road, rail and aircraft noise. These models have been used for the identification of sleep effects due to aircraft noise and railway noise, the selection of criteria for the protection of health, and the consideration of measures to avoid or reduce adverse effects and promote beneficial effects. The noise impact assessment of transportation proposals can use these models to investigate the likely change to sleep on the population and develop measures that directly address the physiological effects caused by noise at night.

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