Predictions of Sleep Disturbance for Different Nighttime Airport Operation Strategies Using a New Markov State Transition Sleep Model

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Summary
To balance benefits and costs of potential airport operation changes such as noise curfews, changes in flight schedules, or flight paths, models are needed which can predict the time varying nature of the effects of aircraft noise on sleep. While a Markov transition model has been developed which predicts the transitions between 6 sleep stages throughout the night (Wake, S1, S2, S3, S4, and REM), it has two limitations. The Markov model was developed based on data from a laboratory study, in which a greater probability of aircraft noise-induced awakenings was found compared to field studies. In addition, the model predicts the same probability of awakening for all aircraft events, regardless of the noise level. To overcome these two limitations, a new Markov transition model was developed using data from a total of 483 nights from 63 subjects who participated in a polysomnographic field study that was conducted around Cologne-Bonn Airport. Similar to the previous Markov model, transition probabilities between sleep stages were calculated using 1st-order autoregressive multinomial logistic regression models. However, in addition to elapsed sleep time, the maximum noise level has been added to the model as an explanatory variable. This new Markov model was used to predict the number of awakenings and the time spent in each sleep stage for different nighttime noise mitigation strategies. The development of the model and differences and similarities in the predictions for the different operation scenarios will be discussed.

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1. Introduction

To predict the impact of noise on sleep there are several existing models that have been developed. The majority though only relate the indoor noise level of single aircraft events to the probability of awakening (e.g. [1], [2], [3]). Also these models assume that the impact of each aircraft event on sleep is independent of any previous events. However, whether an individual awakens to an aircraft event depends on many factors including the sleep stage an individual is in, time of night, acoustical characteristics of the noise, as well as individual parameters such as age. In addition, aircraft noise may not only increase the number of awakenings but affect the depth of sleep specifically and sleep structure in general as well.

In order to better predict potential sleep disruption in communities, models that incorporate these parameters are needed. A model that incorporates a few of these additional parameters has been developed; Basner [4] has developed a Markov state transition model for predicting the impact of aircraft noise on sleep. This model predicts sleep stages during the night. It was created based on data from 125 subjects that took part in a laboratory study which examined the effects of aircraft noise on sleep. Aircraft noise though has been found to have a greater effect on sleep in laboratory studies than in field studies [5], [6], which may be partially due to habituation in communities. Therefore, the model may overestimate the impact of noise on sleep. In addition, in the

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Markov model the probability of transitions between sleep stages is only dependent on whether an aircraft event has occurred. The probability of transitioning between sleep stages is not dependent on the noise level of the aircraft event. Due to these two limitations of the previous model, a new Markov model has been developed. This model was developed based on data from the STRAIN field study conducted around Cologne-Bonn Airport [2] and the probability of sleep stage transitions within the model is dependent on the elapsed sleep time, prior sleep stage, and the indoor maximum noise level of the aircraft event.

Predictions using the developed Markov model have been examined to determine whether the model can predict expected variations in sleep throughout the night. Comparisons have been made between model predictions of hourly sleep stage durations and those observed in the STRAIN dataset. In addition, the model was used to predict sleep stage durations and awakenings for three different flight scenarios, two of which consisted of a ban of flight operations during the middle of the night, the results of these simulations will be described.

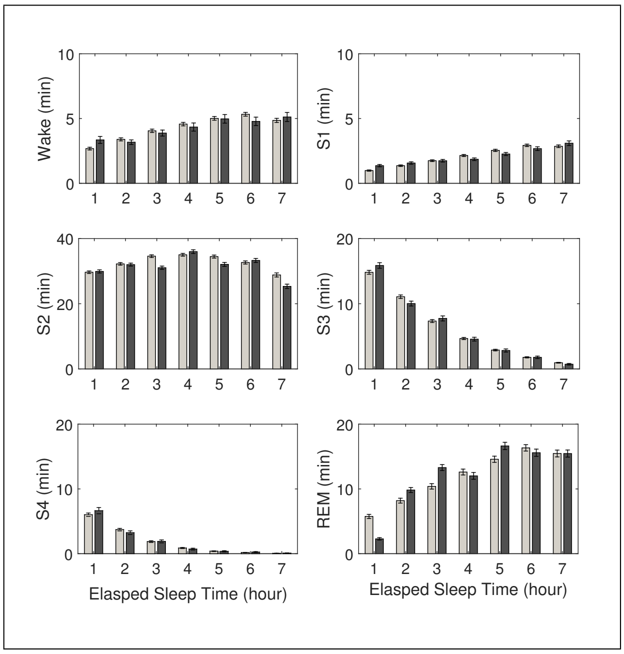

Figure 1. Mean sleep stage durations for each hour of the night. Predicted sleep stage durations (light gray). Observed sleep stage durations in the STRAIN dataset (dark gray). Error bars are the standard error.

2. Methods

The data used for developing the Markov model is from the polysomnographic field study STRAIN conducted by the German Aerospace Center around Cologne-Bonn Airport [2] on the effects of aircraft noise on sleep. Data from 63 subjects for 483 nights was used to develop the model. The Markov model is a 6 state model, which predicts sleep stages 1, 2, 3, 4, and REM (rapid eye movement sleep), as defined by Rechtschaffen and Kales [7], for each 30 second epoch during the night. The probability of transitioning between sleep stages are calculated using 1st-order auto-regressive multinomial logistic regression models. There are 4 regression models; one model is used to calculate the probability of sleep stage transitions when aircraft noise is not present, and there are 3 models used to calculate transition probabilities for 1 1/2 minutes after the start of an aircraft event. The coefficients for the regression models were calculated using the CATMOD procedure in SAS. Within the model the probability of transitioning between sleep stages is dependent on the current sleep stage, time from sleep onset, and the maximum indoor noise level of the aircraft events.

3. Results

3.1. Model predictions of STRAIN dataset

To evaluate the accuracy of model predictions, simulations of the STRAIN dataset were made using the developed Markov model. Sleep stages were predicted for the same number of subject nights, duration of sleep periods, timing of aircraft events, and indoor L_{Amax} levels as in the dataset. One hundred simulations were performed and the mean predicted time spent in each sleep stage for each hour of the night was calculated. The results of the simulations and the mean hourly sleep stage durations observed in the STRAIN dataset are shown in Figure 1. The model was able to reasonably predict the same hourly sleep stage durations as observed in the data. There was one exception in which the model predicted more REM sleep during the first hour of the night.

The probability of being in each sleep stage as predicted by the model was calculated and is shown in Figure 2. The probability of being in each sleep stage was also calculated based on the STRAIN dataset and is shown for comparison. The model predicts a similar increase in the probability of being in Wake, S1, and REM and decrease in probability of being in S3 and S4 with time as observed in the dataset. However, the model is not able to predict the oscillations in probabilities that is apparent in the STRAIN data as the Markov model is based on a 1st-order auto-regressive model, predictions of each sleep stage during the night is only dependent on the previous sleep stage.

3.2. Model predictions for different flight operation scenarios

Predictions of sleep stage durations and awakenings were also calculated for different aircraft noise scenarios. Three scenarios, the same as those used by Basner and Siebert [4], were examined. Scenario 1 has events throughout the night, for Scenario 2 events in Scenario

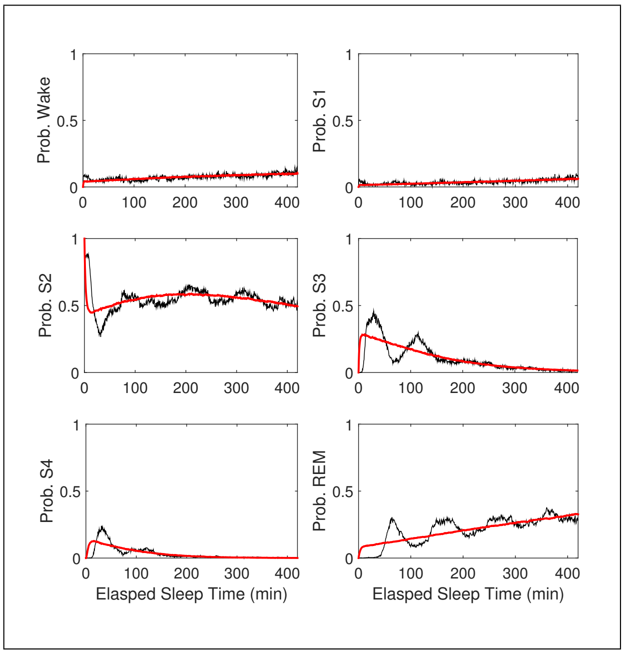

Figure 2. Probability of being in each sleep stage during the night. Predicted probabilities based on 100 simulations (red). Observed sleep stage probabilities in the STRAIN dataset (black).

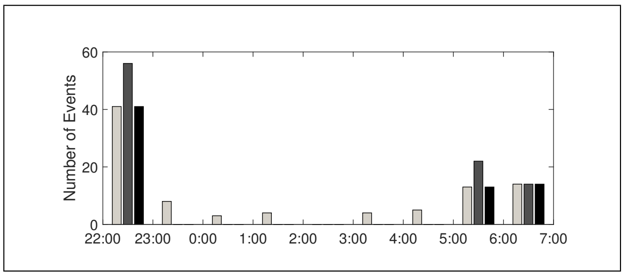

Figure 3. Hourly events for the three flight operation scenarios. Scenario 1 (light gray), Scenario 2 (dark gray), Scenario 3 (black).

1 between 11:00 pm and 5:00 am were rescheduled to periods at the beginning of the night between 10:00 to 11:00 pm and end of the night between 5:00 to 6:00 am, and for Scenario 3 all events between 11:00 pm and 5:00 am in Scenario 1 were banned and not rescheduled to other periods of the night. The number of hourly events for each of the three scenarios between 10:00 pm and 7:00 am are shown in Figure 3.

For the predictions of sleep for the 3 different flight operation scenarios, different times of falling asleep and sleep durations were used. The distribution of values used were based on self-reported in bed times reported by 2278 participants in a survey conducted around Frankfurt Airport [8]. The distributions are shown in Figure 4.

For each of the 3 flight operation scenarios, 1000 simulations were conducted for 125 different sleep onset and sleep duration values. Within each simulation

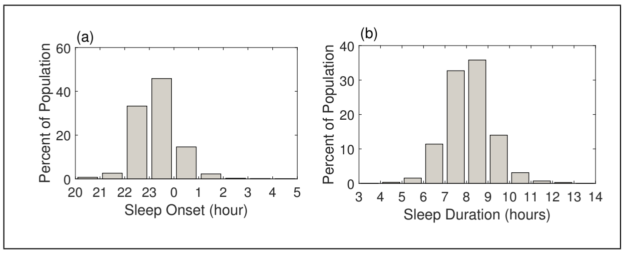

Figure 4. (a) Distribution of sleep onset times and (b) distribution of sleep durations used in the predictions of sleep stage durations for the 3 different flight operation scenarios.

all events were of the same indoor L_{Amax} levels. Simulations were repeated for L_{Amax} levels from 35 to 70 dB(A). The mean sleep durations and number of awakenings due to the aircraft noise events were calculated, the results of which are shown in Figure 5 and Figure 6. The mean values are weighted according to the distributions of sleep parameters that were used.

Time spent awake during the night was reduced in Scenario 2 and 3 when there was a ban on aircraft noise events between 11:00 pm and 5:00 am. However, this reduction only occurred for noise events of 50 dB(A) or higher. Also the reduction in time spent awake was small, the largest difference found was 2.5 minutes between Scenario 1 and 3 when all events were of 70 dB(A). The number of awakenings was also reduced in Scenario 2 and 3, with a maximum difference of 1.6 awakenings found. In addition to awakenings, an increase in time spent in slow wave sleep (stage 3 and 4) was also found for Scenario 2 and 3 compared to Scenario 1. An increase in slow wave sleep was observed for events of 50 dB(A) or higher with a maximum difference of 2.7 minutes between Scenario 1 and 3 when all events were of 70 dB(A).

4. Discussion

This new Markov model was developed to correct 2 limitations of a previous model, it was developed based on data from a field study and the probability of sleep stage transitions throughout the night is dependent on not only the time since sleep onset and prior sleep stage but also the noise level of each aircraft event. To evaluate the accuracy of the model predictions, it was used to simulate the STRAIN field dataset and it was found that the model was able to predict similar mean hourly sleep stage durations and probabilities of being in each sleep stage throughout the night as observed in the dataset. The model though needs to be further validated by simulating additional datasets. The potential impact of noise on sleep for three different flight operation scenarios was also examined using the model. For simulations in which aircraft were of all the same level, a reduction

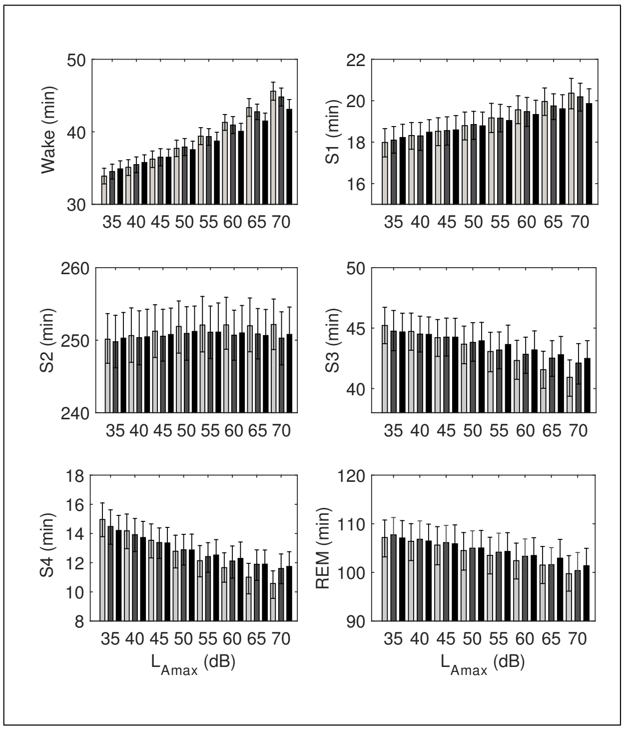

Figure 5. Mean sleep stage durations predicted for the 3 flight operation scenarios, for aircraft noise events of indoor L_{Amax} levels from 35 to 70 dB(A). Error bars represent the 25 and 75 percentiles of the values obtained for the 1000 simulations. Scenario 1 (light gray), Scenario 2 (dark gray), Scenario 3 (black).

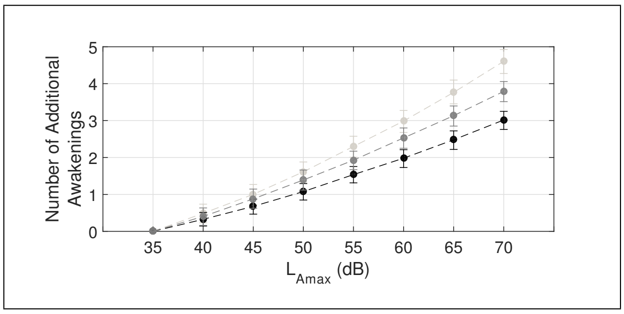

Figure 6. Mean number of additional awakenings compared to the 35 dB(A) noise conditions for the 3 flight operation scenarios for aircraft noise events of indoor L_{Amax} levels from 40 to 70 dB(A). Error bars represent the 25 and 75 percentiles of the values obtained for the 1000 simulations. Scenario 1 (light gray), Scenario 2 (dark gray), Scenario 3 (black).

in time spent awake and an increase in slow wave sleep (stage 3 and 4) when aircraft events were banned between 11:00 pm to 5:00 am was found, however the differences were all less than 3 minutes. While of a different magnitude, previous analysis examining the difference in sleep structure for the 3 operation scenarios using a Markov model [4] developed based on laboratory data, also found little difference between the scenarios. While the results of the simulations conducted in this analysis found only small improvements in sleep structure during the night with the ban of nighttime events, there may be other improvements in sleep that were not predicted and examined in this analysis. In addition, predictions of sleep for more realistic airport noise levels needs to be completed, by first predicting noise contours for an airport and then using the noise levels within the model. Combined with noise prediction tools this model could be useful for examining whether proposed mitigation measures will lead to significant improvements in sleep.

Acknowledgement

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