A comparison of noise-induced sleep disturbance predictions around airports using awakening models and simplified sleep structure based models

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ABSTRACT

Nighttime aircraft noise has been found to increase the number of awakenings as well as affect time spent in different stages of sleep. There are existing models that could be used to predict changes in sleep structure due to noise. However, there is a question of whether the added complexity of these models would result in significantly improved predictions of the number of people impacted by nighttime noise over that predicted by simpler models that exist. In order to examine this question, existing sleep structure models had to be modified to incorporate a noise level dependence, as most only predict normal sleep patterns. Different methods for introducing this dependence were examined in order to reproduce results found in various airport noise studies. In order to make comparisons between community impact predictions from these and existing sleep disturbance models, flight operations data from several US airports were obtained and noise exposure was predicted. To assess sleep impact the number of awakenings and various sleep quality indices were calculated using one or more of: L_{night}, dose-response awakening models, the ANSI/ASA S12.9-2008 Part 6 standard, and the modified sleep structure models. Differences and similarities in the predictions of sleep disturbance for a number of different sets of flight operations are discussed.

INTRODUCTION

In order to predict the effect of nocturnal transportation noise on communities several models have been developed. These models range in complexity from the simplest which are cumulative metrics such as L_{night} to the most complex which is to predict the effect of noise on time spent in different stages of sleep. To develop models and also to decide which to use to predict community impact, predictions from different models need to be compared for a variety of flight operations scenarios. Differences and similarities in predictions need to be evaluated. Also it needs to be examined whether increasing model complexity leads to improved predictions of community impact compared to predictions from simpler models.

Understanding the similarities and differences between model predictions is also important when considering the type of data that should be collected as part of future studies in order to validate proposed models. If survey data is only collected for flight operations in which all models produce very similar results then it will not be possible to highlight the pros and cons of the various modeling approaches. Using flight operations data from different types of airports along with census and community data, sampling strategies for future surveys can be studied and refined so that the right type of data can be collected to enable a comprehensive evaluation of the different models. Of particular interest is gathering data that enables models to be updated and their parameters estimated better, i.e. with less uncertainty (variance).

To examine sleep disturbance model predictions, data was obtained from US airports. Different flight scenarios were created and single and cumulative noise metrics were calculated. Comparisons between noise metric values, predicted number of awakenings and changes in sleep structure for the different scenarios using several existing models were made.

SLEEP MODELS

The use of $L_{night,outside}$ was examined. In the World Health Organization's Night Noise Guidelines for Europe (WHO 2009) it was recommended that outside noise levels be below 40 dB at night to prevent adverse health effects. As such a limit would be difficult to obtain a target goal of 55 dB was proposed. One limitation though of using L_{night} as a predictor of sleep disturbance is that the same L_{night} could be obtained from different combinations of numbers and levels of aircraft events. Therefore, Basner et al. (2009) have suggested using number of events to supplement L_{night}.

Several awakening models were also examined. The most common type of awakening models are dose-response relationships which relate the indoor noise level of the event measured with either L_{Amax} or *SELA* to the percent awakened (e.g. Basner et al. 2006; FICAN 1997). There is variation between models in the predicted percent awake for a given noise level. One of the primary reasons for this variation is differences in how sleep disturbance was quantified. For example, the FICAN model is based on behavioral awakenings (only captures longer duration awakenings) but is an upper limit of the data it is based on, while the model developed by Basner et al. (2006) is based on awakenings measured by using polysomnography which is a more sensitive measure of awakenings. Also a standard, ANSI/ASA S12.9-2008, has been developed for quantifying noise-induced sleep disturbance. It is based on behavioral awakening dose-response curves and it predicts the percent of the population awakened at least once during the night. In the ANSI standard two models are given; a model in which the probability of awakening is only dependent on noise level and a model that has both noise level and time dependence.

While aircraft noise increases the number of awakenings, it can also change individuals' sleep structure, including reducing the time spent in Rapid Eye Movement (REM) and Slow Wave Sleep (SWS) (Griefahn et al. 2008). There are a few models that could be used to predict these changes. A Markov model based on an autoregressive multinomial logistic regression has been developed by Basner (2006) using data from a DLR laboratory study. It predicts the probability of moving from one stage to another. The output of the model can be used to construct a hypnogram showing the sleep stages an individual is in during the night. Also, there is the potential to use nonlinear dynamic sleep models for predicting changes in sleep structure. This type of model has been used to predict normal sleep patterns and could potentially be adapted to predict noise-induced sleep changes (e.g. Massaquoi & McCarley 1992). The output from both the Markov and nonlinear dynamic models could be used in conjunction with sleep quality indices, which are functions of parameters including the number of awakenings, duration spent in different stages of sleep, and sleep onset latency (e.g. Basner 2006; Griefahn et al. 2008), to predict the total effect of noise on sleep.

APPROACH

In order to examine sleep disturbance model predictions for different scenarios, flight operations data were obtained for two US airports. The obtained data included flight paths, number of arrivals and departures, types of aircraft, and timing of events. For each airport a list of aircraft present in approximately 90 % of the operations was generated. Noise simulations for this consolidated list of aircraft on multiple flight paths, were completed using the Federal Aviation Administrations Integrated Noise Model (INM) version 7.0b. The data obtained from these simulations consisted of L_{Amax} and *SELA* levels for single aircraft events for a grid spacing of 0.1 nautical miles (nmi). Different operations scenarios were generated and the single event noise levels were used to calculate sleep disturbance using the different models described above. The scenarios are not exact representations of the operations typically found at the airports from which data was obtained. The airports are referred to as Airport A and Airport B throughout this report.

MODEL PREDICTIONS

A baseline operations scenario was created for each airport. For Airport A the baseline scenario is 150 operations and for Airport B it is 281 operations. The aircraft, runways and flight paths used were assigned randomly based on the percent use calculated from the original files. The percent awakened at least once was calculated using the method as described in the ANSI standard, however different dose-response awakening models were used including the one in the ANSI standard and the FICAN and Basner et al. (2006) model. As the sleep/awakening model predictions are based on indoor noise levels, an outdoor to indoor noise attenuation of 25 dB was used. This level of attenuation is similar to those found or used in various studies (WHO 2009). The results shown in Figure 1 (a,b,c) are for the baseline scenario for Airport A in which the operations are on two parallel runways, while in Figure 1 (d,e,f) 25 of the 150 operations were assigned to a third runway which crossed the other two. A smaller percentage of the population is predicted as being awakened at least once when using the ANSI standard, particularly along the cross runway than when using the FICAN or Basner et al. model.

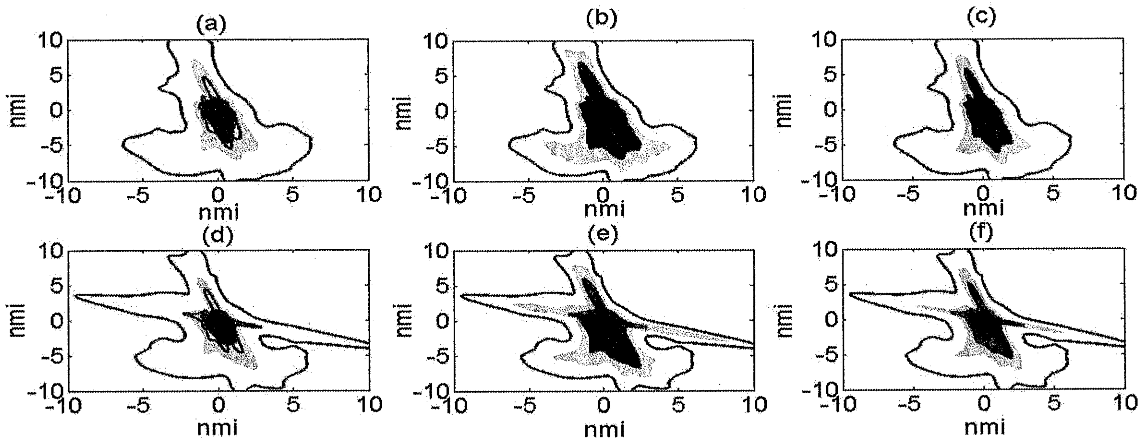

Figure 1: Gray-scale shading indicates percent awakened at least once.
Black to dark gray 75 %, dark gray to light gray 50 %, and light gray to white 25 %.
(a,b,c) Scenario 1 and (d,e,f) Scenario 2. (a,d) ANSI, (b,e) FICAN and (c,f)
Basner et al. model. Red contours are the 40 and 55 dB $L_{night,outside}$ contours.

In order to examine the number of awakenings that would occur in the community, population data from the 2000 US census was obtained for the two airports that were examined. The total population in each 0.01 nmi^2 block for the region of interest was calculated and then multiplied by the percent awakened at least once which was predicted using Basner et al.'s dose-response model. The results are shown in Figure 2. The $L_{night,outside}$ contours are plotted for comparison. At Airport A there are few people residing within the 55 dB contour. For both Airport A and B, those living out to the 40 and 45 dB L_{night} contour are still experiencing sleep disturbance Therefore, using the 55 dB L_{night} contour alone would result in numerous communities erroneously being classified as unaffected by nocturnal noise.

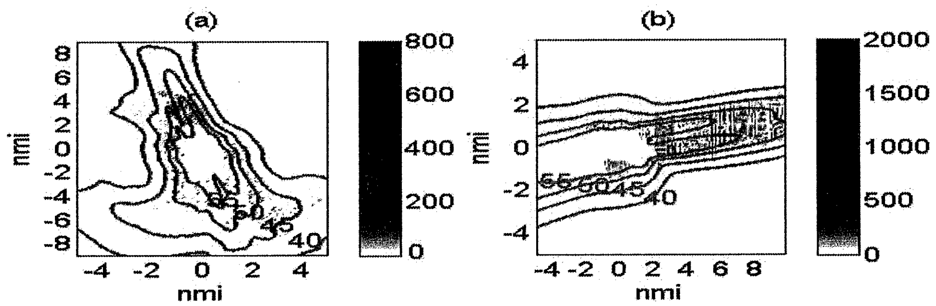

Figure 2: $L_{night,outside}$ contours (red) and number of people awakened at least once (gray to black) predicted using Basner et al.'s dose-response relationship for (a) Airport A and (b) Airport B.

Both the ANSI standard and Basner's Markov model contains a time dependence. In order to examine similarities and differences in model predictions for different distributions of aircraft events during the night six different time scenarios were examined. The six scenarios are shown in Figure 3. Scenarios 1 and 4 are similar to nighttime operations at the airports for which data was obtained. The other scenarios were chosen to emphasize the difference between models. A defined number of aircraft events were assigned to each of the 8 hours of the night and within that hour the events were randomly assigned. For simplicity when performing these simulations it was assumed all individuals went to sleep at the same time and that the duration of sleep was 8 hours.

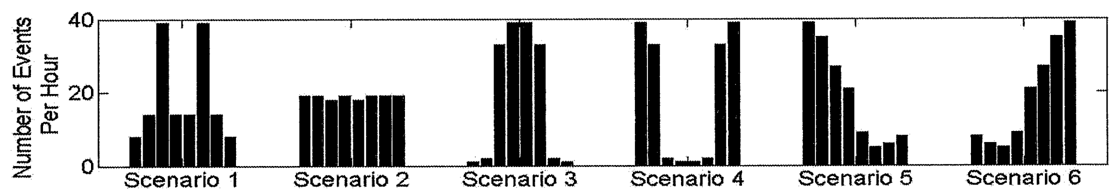

Figure 3: Six nighttime scenarios that were examined. Each bar represents the number of events during an hour of the night. There are eight bars per scenario representing each hour from 11 pm to 7 am.

In the ANSI standard, the probability of awakening increases throughout the night. It is lowest at the beginning and highest at the end of the night. Therefore, Scenarios 1, 2 and 3 in which the events were either evenly distributed throughout the night or most of the events were in the middle of the night, produced similar numbers of awakenings. The largest difference in the predicted number of awakenings was between Scenario 5 in which most of the events were at the beginning of the night and Scenario 6 in which most of the events were at the end of the night. A comparison of the average number of awakenings for each of the six scenarios is shown in Figure 4.

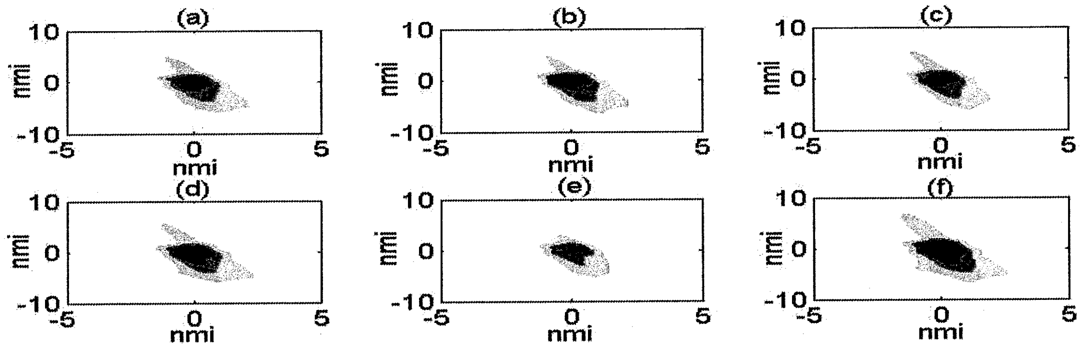

Figure 4: Model predictions for Scenario 1 through 6, labeled (a) thru (f) respectively using the ANSI dose-response model. Gray-scale shading indicates the average number of awakenings. Black to dark gray 1.5, dark gray to light gray 1.0 and light gray to white 0.5 awakenings.

In order to examine model predictions with Basner's Markov model for the different time scenarios, first a noise level dependence had to be added to the model. The model only accounts for whether a noise event occurs but not for changes in sleep structure for events of different noise levels. A noise level dependence was added in a similar fashion as previously examined (McGuire & Davies 2008) in that the values of the noise model coefficients were varied with noise level. However, this time they were varied quadratically in order to obtain an increase in awakenings with noise level which matched Basner et al.'s (2006) dose-response relationship. The coefficients that define the time dependency in the model were not varied with noise level.

After adding a noise level dependence to the model, simulations for the six different time scenarios was completed. Smoothed contours indicating the average number of noise induced/additional awakenings for each scenario are shown in Figure 5. The results are opposite to those found in the ANSI standard. There are more noise-induced awakenings if the majority of aircraft events are at the beginning of the night. This difference is partly due to the time dependent coefficients of the Markov model; for the baseline no-noise model the probability of being in stage wake increases throughout the night, however, for the first and second noise model the probability of being in stage wake decreases with time. This decrease in probability of noise-induced awakenings is supported by other models that have a time dependence (Brink et al. 2008). Overall though the difference in the number of noise-induced awakenings for the different scenarios was small.

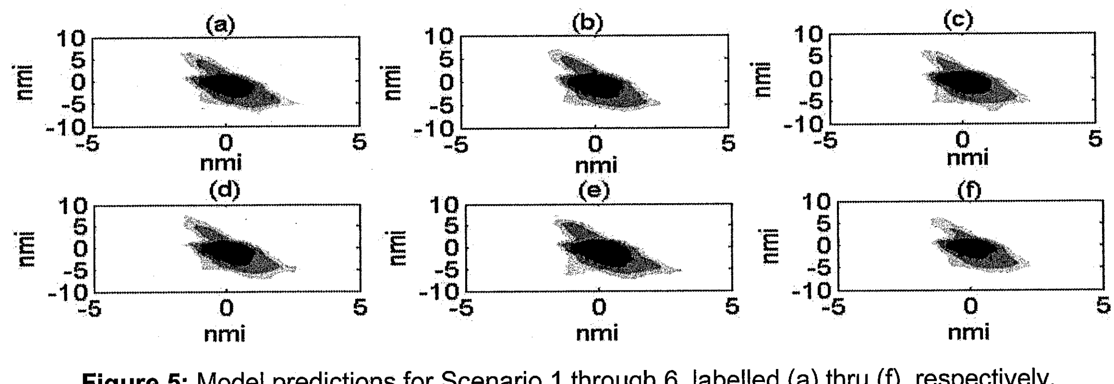

Figure 5: Model predictions for Scenario 1 through 6, labelled (a) thru (f), respectively, using Basner's Markov model with level dependence. Gray-scale shading indicates the average number of noise induced awakenings. Black to dark gray 1.5, dark gray to light gray 1.0 and light gray to white 0.5 awakenings.

In addition to differences in the predicted number of awakenings for the different time scenarios, there are also differences in the duration spent in different stages of sleep. A sleep quality index was calculated for the six different time scenarios. This index was developed by Basner (2006) and linearly weights the durations of the different stages of sleep, with Stage 4 having the highest weighting and Stage 2 having the lowest. Therefore, a lower value of the sleep quality index coincides with worse sleep. The differences in values of the sleep quality index for the different time scenarios are shown in Figure 6 and once again are quite small, however the sleep quality index is the lowest for the scenario in which most events are at the beginning of the night as time spent in slow wave sleep is the most affected for this scenario.

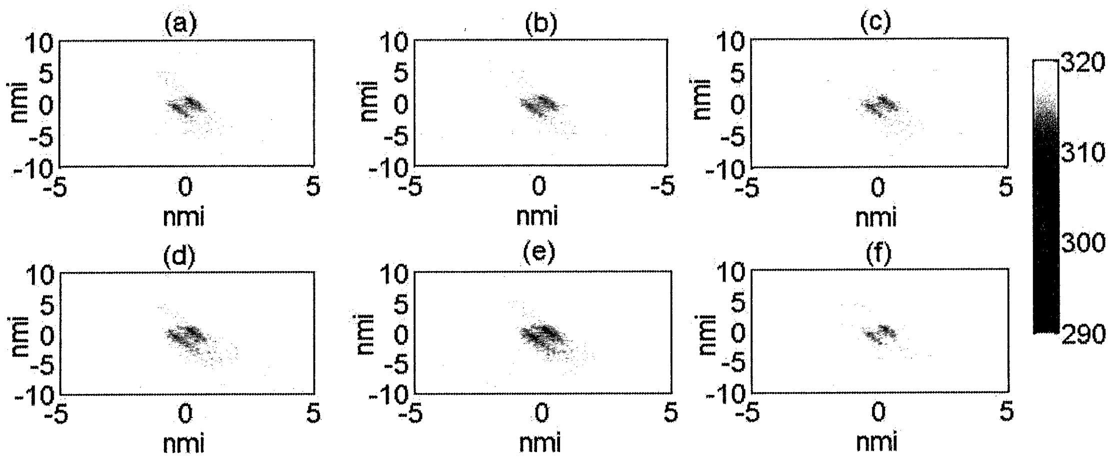

Figure 6: Sleep Quality Index for Scenario 1 through 6, labeled (a) thru (f) respectively calculated using Basner's Markov Model with added noise level dependence.

While the changes in sleep structure in the simulations that were conducted are small, predicting these changes does aid in differentiating the impact of different operations scenarios. In addition, most sleep studies have been conducted in healthy populations and it is unknown how much the sleep structure of more vulnerable groups may be affected by noise. Sleep structure models are a useful tool for exa-,mining the effect of noise on sleep, but there is a need to further develop and validate these types of models.

One aspect of Basner's Markov model that was further examined is the ability to estimate the large number of coefficients of the model, as ideally this model should be further validated using data from other studies. There are 35 coefficients per model and there are four models, one baseline model which is used when there are no noise events and three noise models as it was determined that aircraft noise affects one and a half minutes of sleep. One thousand simulations of Basner's laboratory study consisting of the same number of person-nights (1,008), and number and timing of events were performed in order to determine the ability to re-estimate the coefficients of the model. The coefficients of the simulated datasets were calculated using *mnrfit* in Matlab, which uses an iterative weighted least squares approach for calculating the coefficients. It was found from performing these simulations that several sleep transitions, which are listed in Table 1, never occurred. This is due to certain transitions rarely occurring in normal sleep, for example transitioning from wake directly to stage 4. The coefficients for which there were a nonzero number of transitions could be re-estimated due to sufficient data.

Table 1: Sleep stage transitions that did not occur in simulations of Basner's Laboratory Study (0 - 4 wake through stage 4, 5-REM)

Baseline	1st Noise Model	2nd Noise Model	3rd Noise Model
s_1 to s_4 s_5 to s_4	s_0 to s_4 s_1 to s_4 s_4 to s_5 s_5 to s_3	s_0 to s_4 s_1 to s_3 s_1 to s_4 s_4 to s_5 s_5 to s_3 s_5 to s_4	s_1 to s_4 s_4 to s_1 s_4 to s_5 s_5 to s_3 s_5 to s_4

Due to the number of transitions that do not occur, and the fact that stage 1 is a transition stage and stage 3 and 4 are often combined and referred to as slow wave sleep a reduced model in which there were only four stages (wake, stage 2, slow wave sleep, REM) was created. To calculate the coefficients, simulated datasets were created using Basner's Markov model and then coefficients for a reduced model were calculated based on the simulated datasets. Using the reduced model there were two transitions that never occurred, the transition from REM to slow wave sleep for both the second and third noise model. This suggests that a further reduction of the model should be explored, so that in the future a dependence on noise level as well as other personal or noise characteristics could be added to the model such that the coefficient values could be estimated with an appropriate amount of data.

Another aspect that was examined was the difference in predictions using Basner's Markov model which does not predict the cyclic oscillation between REM and NREM sleep and predictions using a nonlinear dynamic model of sleep which can predict this behavior (Massaquoi & McCarley 1992).

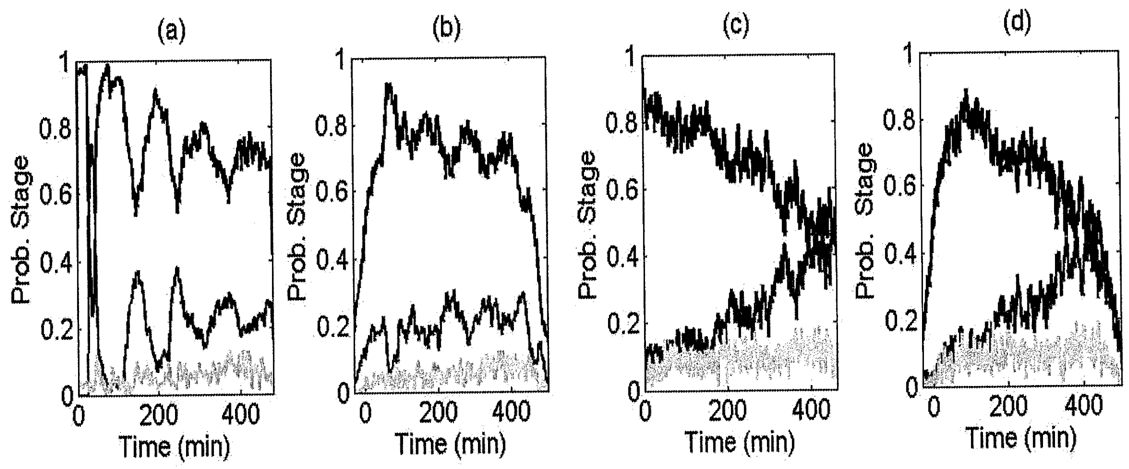

Figure 7: Probability of being in NREM sleep (black), REM sleep (dark gray) and Awake (light gray), predicted using (a,b) the Massaquoi and McCarley model and (c,d) Basner's Markov model. (a,c) It was assumed everyone retired to bed at 11:00 pm. (b,d) A Gaussian distribution for time of retiring was assumed with a mean of 11:00 pm and standard deviation of 30 minutes.

One-hundred simulations were performed with both models and the effect of different times of retiring on predicted probabilities of being in different sleep stages were examined. The results are shown in Figure 7. The cyclic nature of time spent in different stages of sleep is largely attenuated when assuming different times of retiring. However, the nonlinear models may still provide useful information on sleep onset latency, and latency to slow wave sleep and REM sleep.

CONCLUDING REMARKS

The ANSI standard, as it is based on behavioral awakening data, predicts a low number of awakenings compared to other dose-response models, and it was found that this could be problematic when there are a few flights on a specific runway or flying over a specific area. Also the ANSI standard and the Markov model were found to have an opposite dependence on time and therefore have conflicting predictions. The variation in the predictions of number of awakenings and impact on sleep structure for different distributions of events during the night was found to be small. However, before questioning the use of sleep structure models there is a need to examine the change in predictions for a wider variation in flight operations and also the change in sleep for more sensitive populations.

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