A case study on the validation of models that predict the impact of aircraft noise on sleep

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The impact of aircraft noise on sleep disturbance is not accurately assessed by cumulative noise metrics that are often used to predict community impact, such as $L_{dn,}$ because sleep disturbance is highly dependent on the noise level of individual events. Most existing sleep disturbance models are dose-response relationships that relate the noise level of individual events, as measured by *SEL(A)* or L_{Amax}, to the percent awakened, and independence of responses to individual events is assumed. There are a few models that also incorporate additional parameters such as time of night and noise sensitivity, and some that predict the impact of noise on sleep structure. An approach to modifying an existing sleep transition model to incorporate noise level dependency is described. Data was collected from a number of sleep disturbance studies and comparisons were made between the responses in the survey, the modified sleep transition model's predictions of awakenings, and those from a simpler awakening model.

1 Introduction

The primary method that has been used for assessing the impact of aircraft noise on sleep is to evaluate the percent awakened by individual aircraft events. Dose-response relationships which relate the indoor noise level to the percent awakened are typically used. However, from recent research on sleep disturbance it appears that additional factors such as noise sensitivity [1] and rise time of the event [2] should also be considered. Noise events at night may also result in changes in sleep structure, other than number of awakenings, and this may impact health as well as sleep quality. For example, slow wave sleep (stages 3 and 4) may be particularly important for physical restoration; a reduction in time spent in slow wave sleep could potentially increase the risk for developing health problems such as diabetes [3]. A model developed by Basner [4], does predict the effect of noise on sleep structure, but unlike the awakening models, it does not include the effect of noise level, just its presence, or not. It does include time-of-night effects but does not include such factors as noise sensitivity or other sound characteristics. It is noted, however, that the effect of noise level on sleep has been explored by Basner and accounted for in other models [5].

The outputs from Basner's sleep transition model can be analyzed to determine change in sleep structure and number of awakenings under different noise scenarios. The research described in this paper was focused on examining: (1) a method for modifiying one of Basner's models to include noise level, (2) the differences between predictions from the simpler awakening models and the awakenings predicted when using the modified sleep transition model, and (3) how the predictions from the models compare with results of three sleep disturbance surveys.

2 Sleep transition model

Basner's sleep transition model [4] is based on the data from a laboratory study conducted at the DLR Institute of Aerospace Medicine. 128 people took part in the study, 16 people served as a control group, and 112 people were in the experimental group. Those in the experimental group were presented with 4, 8, 16, 32, 64, or 128 aircraft events on a given night. The events were evenly spaced and only events of one noise level were presented on a particular night. Noise levels of the events presented during the study ranged from a maximum level of 45 to 80 dB(A).

Basner built four autoregressive multinomial logistic regression models based on this survey data. Each has the structure:

$$p(s_i \mid s_j) = \frac{e^{a(s_i)+b(s_i).t+c(s_j,s_i)}}{\sum_{i=0}^{5} e^{a(s_i)+b(s_i).t+c(s_j,s_i)}} \quad (1)$$

They predict the probabilities of moving from one sleep stage (s_j) to another (s_i) at the end of each epoch (30 second segment) of sleep. These transition probabilities are dependent on the current sleep stage and the epoch number (t), which has a value between 1 and 820. The values of the coefficients when i equals 2 are zero however, because stage 2 is the reference stage for the four models.

There is a baseline model, which is used to assess transitions when no aircraft events occur within a certain epoch. Also there are three noise models; they have the same structure as the baseline model but with different coefficients. Basner found that an aircraft event directly impacts three consecutive 30 sec epochs of sleep; the first of these epochs being the 30 sec segment in which the noise event starts. Even though the laboratory study involved aircraft events of different noise levels, all three of the noise models are invariant of level. However, if noise level does play a role, then Basner's noise models could perhaps be thought of as predictors of the transitions caused by the average of the noise levels used in the survey.

3 Noise level dependent model

Noise level dependency is reported in numerous sleep studies [6,7,8,9,10] which have resulted in awakening models that vary with event level, e.g., Anderson and Miller [1], Passchier-Vermeer *et al.*[10] and Finegold and Elias [11]. Therefore, an approach to adding a level dependence to Basner's model has been explored. Each of the regression coefficients of the three noise models have been made a function of noise level. As a first approximation, it was assumed that the relationship between noise level (in dB) and the value of a particular coefficient was linear. The linear equation for each coefficient was defined based on the two points given in Basner's model. The first point was the baseline model coefficient value which corresponded to a noise level of 30 dB(A), which was the background noise level during the study. The second point was a coefficient of one of the three noise models which was considered to correspond to an A-weighted sound exposure level (*SEL(A))* of 63.3 dB(A). This event level was estimated by taking the average of the L_{Amax} levels for each of the noise events that subjects were exposed to in the study and using an approximate relationship between L_{Amax} and $SEL(A)$ [12]. It was decided to use $SEL(A)$ instead of L_{Amax} because that is the metric used in many of the awakening models and also the metric used by Fidell when analyzing his sleep disturbance data [7,8]. An example of the change in the coefficient values with level is indicated in Figure 1. The coefficient values plotted in the figure are used when determining the probability of a transition from Stage 1 to the different sleep stages.

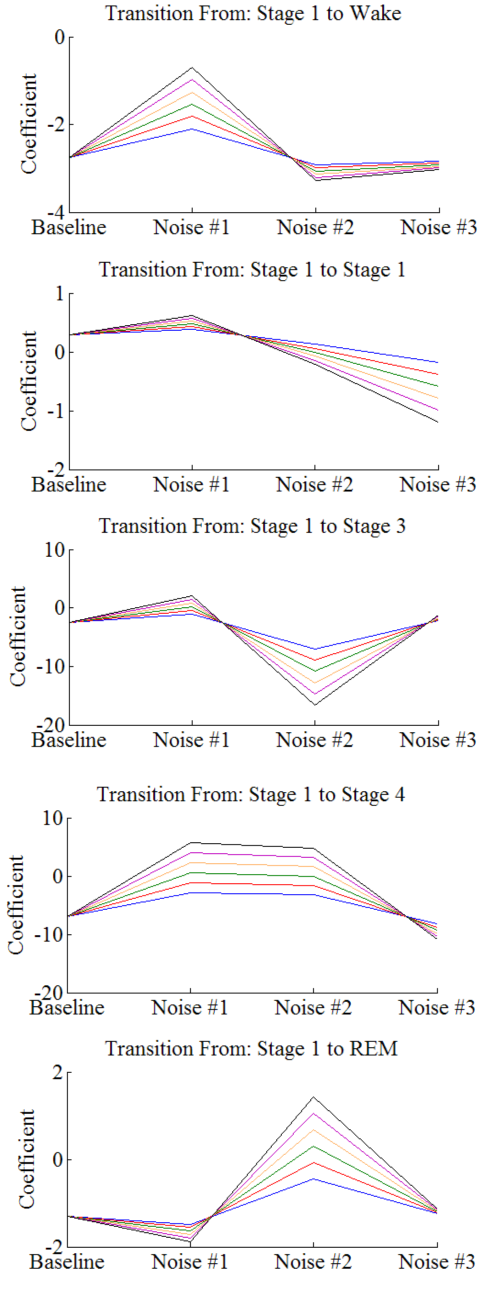

Fig.1 Variation in coefficient values with noise level for the three noise models, 53 dB (blue), 63 dB (red), 73 dB (green), 83 dB (yellow), 93 dB (purple), 103 dB (black).

The resulting variation in the probabilities of transitions between different sleep stages due to noise level differences is shown in Figure 2. The probabilities shown in the figure are the average of the probabilities that occur throughout the night, since the values do vary with time from sleep onset. These probabilities were determined by using coefficients of the first noise model. Most of the changes in probabilities follow expected trends. For example, as the noise level increases, so does the probability of changing from a particular sleep stage to stage wake, while the probability of transitioning from a lighter stage of sleep such as stage 1 or 2 to slow wave sleep decreases with increased noise level. However, an unexpected increase in probability with noise level did occur for transitions from REM to Stage 4 and the probability of a transition from REM to stage Wake was found to decrease for high noise levels.

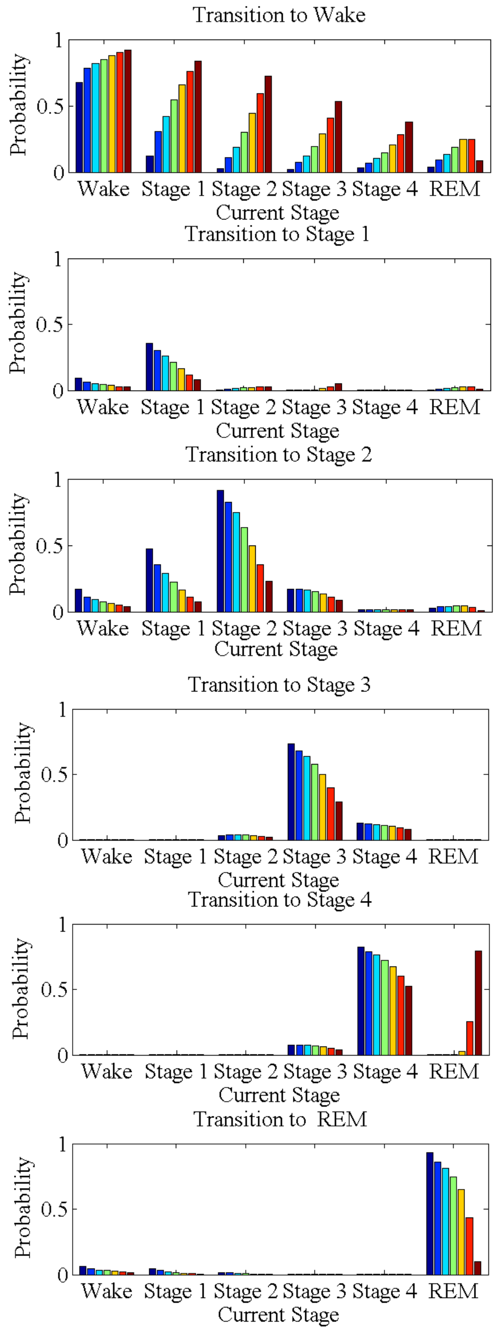

Fig.2 Comparison of the probability of transitions between stages for different noise levels. Baseline model (dark blue), the remaining bars represent noise levels in increments of 10 dB from 53 to 103 dB.

4 Estimation of model coefficients

The noise level dependent model was used to simulate the responses of subjects exposed to the same sequences of noise events as the subjects in Basner's study. The simulation data was then used to estimate the coefficients of

Basner's models, i.e., the models without the noise level dependency, to compare the model coefficients he estimated from his subjects' responses with those that we estimated from the simulated data. Each simulation of the study produced the same amount of data that Basner used in his estimation. The coefficients of the multinomial logistic regression models were calculated by using the *mnrfit* command in Matlab.

The process of creating a simulated dataset and calculating the coefficients of the regression model was repeated 40 times to assess the variation in parameter estimates. The mean and 5 and 95 percentiles of the estimated values were calculated and compared to the original values. In Figure 3, the estimated and original coefficients for the first noise model are shown.

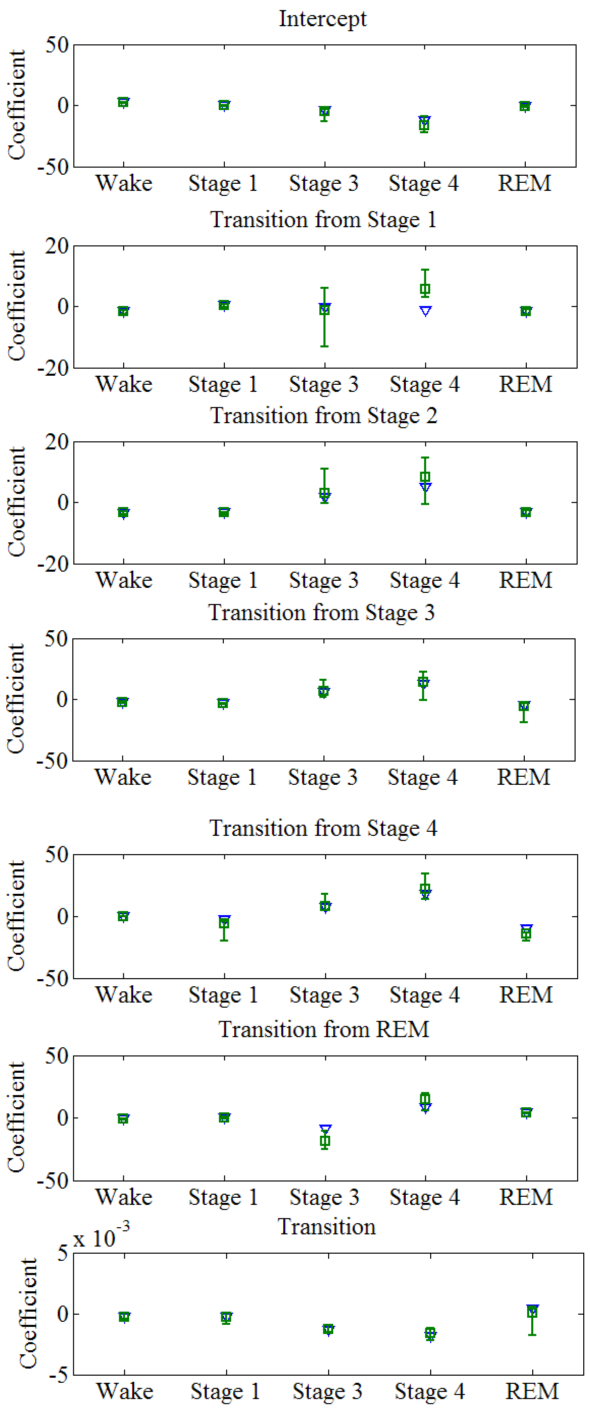

Fig.3 Comparison between the original coefficients of the first noise model (blue triangle) and the estimated coefficients (green square).

The values of the coefficients estimated from the simulation data were within error bounds of the values of the original coefficient values. A few exceptions did occur, however, this was typically due to the fact that certain transitions, such as from stage 1 to stage 4 are unlikely to occur and therefore there was limited data available for estimating these coefficients. Similarly, the estimation of these coefficients was problematic in Basner's study because the experimental data suffers from the same limitations as the simulation data. Similar results to those shown for the first noise model were obtained for the other two noise models as well. Therefore, the data from the simulations of the noise level dependent models result in models consistent with those estimated from the experimental data.

5 Survey data comparison

The question arises, how well do predictions made using Basner's model, with incorporated noise level dependence, relate to findings from field survey data? Data from three sleep disturbance studies conducted by Fidell *et al.* [7,8] were used to investigate this. The field studies were conducted around Los Angeles International Airport and Castle Air-Force Base, Denver International and Stapleton International, and DeKalb-Peachtree airport. In these surveys sleep disturbance was primarily assessed by measuring behaviourally confirmed awakenings, i.e., subjects pressed a button when they were awoken by noise.

With this survey data it is not possible to perform a detailed examination of whether the noise dependent transitions between stages, as predicted by the models, are accurate. However, the data can be analyzed to examine awakenings and thus comparisons can be made between the number of conscious awakenings in the study and those that would be predicted by the models. For this analysis a conscious awakening was defined as an awakening lasting more then two minutes [9].

The time that events occurred relative to the time a subject retired and the indoor *SEL(A)* level of each event were available from the survey data. In addition, as part of the survey, subjects evaluated in a questionnaire they completed the following morning, the time it took them to fall asleep the previous night. This information was used to determine when an event occurred relative to the onset of sleep or first occurrence of stage 2, which is the point during sleep at which Basner's model predictions begin.

When comparing Fidell's data to Basner's model predictions it was decided to combine the data from all three surveys. When the surveys were assessed individually there was limited data available at some noise levels. For example, in the DeKalb-Peachtree survey there was limited data for *SEL(A)* levels below 70 dB(A). For all of the surveys, there was limited data for high *SEL(A)* values above 90 dB(A). To compare awakenings for a wide range of *SEL(A)* levels the data needed to be combined to reduce uncertainty in the predicted percent awake.

Basner's model, with incorporated noise-level dependence, was then used to create simulated responses for the same night-time scenarios as the surveys. Once the simulation was completed, the sleep-stage data was analyzed to compute the number of conscious awakenings for each

SEL(A) level . Only conscious awakenings which occurred within a minute and half of a noise event were counted.

When the simulation of Fidell's surveys was made, an unexpected decrease in percent awakened occurred for noise levels above 95 dB(A). This decreasing trend was believed to be due to the large increase in probability, with noise level, for transitions between REM and Stage 4 and the decrease in the probability of transitioning from REM to Wake for noise levels above 93 dB. To reduce the probability of moving from REM to Stage 4, the corresponding coefficient value of the first noise model was decreased. It is important to note that this coefficient value was not estimated well by the original model, as this transition would not occur often during sleep.

A simulation of Fidell's surveys was made, with the altered noise model, and it was found that a decrease in percent awakened with higher noise levels no longer occurred. In Figure 4, a comparison is made between the results of one simulation with this noise level dependent model and the original survey data. In addition the dose-response relationship determined by Passchier-Vermeer *et al.* [13] is shown. This dose response-relationship has been found to relate well to this set of survey data when only considering noise level and number of awakenings [14].

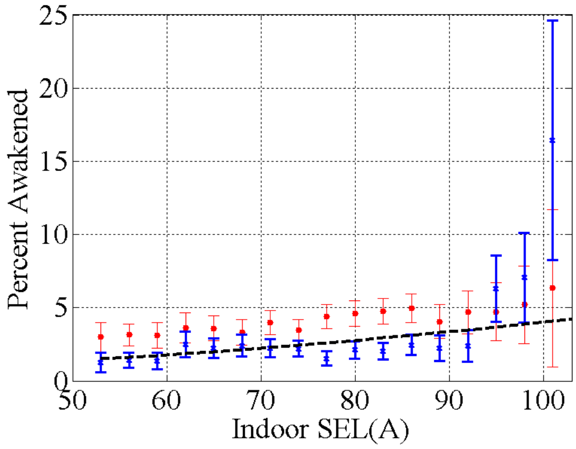

Fig.4 Comparison of Basner's model, with noise level dependence (red circles), Fidell's survey data (blue x) with 95% confidence intervals and Passchier-Vermeer *et al.'s* dose-response relationship (dotted line)

Basner's model, with noise level dependence, was found to over predict the number of awakenings in the survey data. The total number of awakenings predicted by the model is approximately twice that of the survey data. However, when assessing the difference in predicted awakenings for sound exposure levels below 90 dB(A) the variation is never more then 4%. A larger variation does occur for higher *SEL(A)* levels because there is not a lot of survey data for these levels. This is reflected by the large confidence intervals for the percent awakened at these levels. In addition, the prediction from the modification of Basner's model does have a small increase in awakenings with noise level, which is similar to Passchier-Vermeer *et al.*'s awakening model.

6 Laboratory versus field survey

The differences in predictions between the model, which is based on laboratory data and the survey data, bring up an important factor that may need to be accounted for when building a more comprehensive sleep disturbance model.

In comparisons of results from field studies and those from laboratory studies, it has often been observed that a higher percentage of people will be awakened in a laboratory setting than in the field. One explanation for why this difference in awakenings occurs is that people are more comfortable in their own home and also that they have habituated to the noise [15]. Pearsons *et al.* [12] developed separate dose-response relationships for the two types of environments. These relationships predict that a much greater percent of people will be awakened in the laboratory then the field for events of the same noise level. For example, for an *SEL(A)* level of 80 dB, 33% of people in a laboratory study would be awakened while only 4 % in a field would be.

In contrast to Pearsons *et al.*'s results, a study conducted by Skånberg and Öhrström does not support the concept that there is a difference between the two testing environments [16]. They determined that when subjects were exposed to road traffic noise, the number of awakenings that occurred in the laboratory and field were similar. Awakenings measured in the two environments were also found to agree in the 1999 study on the effect of aircraft noise on sleep by Flindell *et al.* [17].

While in some cases the laboratory and field data agree, there are clearly times when they do not; this clearly warrants further examination. It may be possible, with further study, to assess and quantify factors, in addition to noise, that affect sleep disturbance and incorporate those into a more comprehensive sleep disturbance model.

7 Conclusion

The purpose of this analysis was to examine a method for adding noise dependence to a model developed by Basner from laboratory data. The motivation for this was to adapt the model to reflect the increased awakenings with noise level reported in many sleep awakening studies and incorporated into many awakening models. The attraction of a model that predicts sleep stage rather than awakenings alone is that a better understanding of the impact of noise can be assessed from such models.

By using Basner's baseline and three noise presence model coefficients, simple linear relationships between coefficient values and noise levels were developed. To verify that the predictions from these noise level dependent models produced results consistent with those reported by Basner, it was shown that a model similar to Basner's could be estimated from the data simulated using the new model. It was noted, that a much larger data set is needed to estimate coefficients well for situations that do not occur very often. When using the level-dependent model to predict observed conscious awakenings in field studies, it was found that an unexpected decrease in percent awakened occurred for higher noise levels. This decrease was determined to be the result of a high probability for transitions from REM to Stage 4 for high noise levels. It was found that by altering the corresponding coefficient value of the first noise model, the decreasing trend in percent awakened no longer occurred. Further examination of the change in transition probabilities with noise level though is still needed. With the altered noise model, differences were still found between model predictions and survey data, however, these differences were only large at higher noise levels.

To develop a more comprehensive sleep disturbance model, factors that impact subjects' sleep, other than noise, also need to be assessed and modelled, e.g., the lack of familiarity with the laboratory setting or the acclimatization within the home setting should be quantified. A simple approach would be to develop a laboratory-setting model and a field model. While the proposed model appears promising in terms of predicting awakenings, there is currently insufficient data available to validate the detailed predictions of such a model.

Acknowledgments

The authors would like to thank the FAA/NASA/Transport Canada PARTNER Center of Excellence for providing funding for this research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the FAA, NASA or Transport Canada. The authors also wish to thank Larry Finegold who provided the data for the three U.S. sleep disturbance surveys used in this analysis.

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