Markov State Transition Models Based on Autoregressive Multinomial Logistic Regression for the Prediction of Changes in Sleep Structure Induced by Aircraft Noise - The German Aerospace Center Study

Mathias Basner[1] and Uwe Siebert[2]

[1]Institute of Aerospace Medicine, German Aerospace Center (DLR), Cologne, Germany [2]Institute for Technology Assessment, Massachusetts General Hospital, Harvard Medical School, Boston, U.S.A.

ABSTRACT

PURPOSE By dividing polysomnographic recordings into intervals of 30 sec, human sleep can be classified in six distinct states: Awake, stages 1&2 (light sleep), stages 3&4 (slow wave sleep, SWS), and rapid eye movement (REM) sleep. The sleep states differ in their contribution to the restorative power of sleep. Environmental noise is a potential disruptor of the sleep process and may cause changes in the structure of sleep. The goal of this study was to predict changes in total sleep structure depending on sound pressure levels and time patterns of aircraft noise events (ANE).

METHODS In four laboratory studies with 128 subjects lasting from 1999 to 2003, the Institute of Aerospace Medicine of the German Aerospace Center (DLR) investigated the influence of aircraft noise on human sleep. Quiet baseline nights of 125 subjects were used to build and validate a model for the simulation of noise-free nights based on autoregressive multinomial logistic regression. Data of 33,000 ANE and related events were used to incorporate the effects of ANE on transition probabilities. Three noise scenarios (see results) with constant maximum sound pressure levels of 65 dB(A) were compared regarding their impact on total sleep structure.

RESULTS A second order autoregressive model fit the validation criteria best. Comparison of mean sleep stage fractions of baseline nights and 10,000 first-order Monte Carlo trials showed good agreement (model vs. raw data: Awake -0.7%, S1 +27.5%, S2 +0.5%, S3 +2.5%, S4 –8.8%, REM –1.5%). Noise restriction between 11 pm and 5 am (scenario 2: 59.3 min SWS, 47.2 min awake) revealed clear benefits compared to unrestricted traffic (scenario 1: 43 min SWS, 63.5 min awake), although these benefits were reduced if the traffic that formerly took place between 11 pm and 5 am was rescheduled to the time before and after the silent period (scenario 3: 58 min SWS, 54.2 min awake).

CONCLUSIONS It was possible to validly reproduce key features of noise-free baseline nights with a Markov state transition model based on multinomial autoregressive logistic regression. The extension of the model based on extensive data on the reactions to ANEs allows for the comparison of sleep structures induced by different noise patterns and may serve as a valuable tool for structuring nocturnal air traffic and for political decision making.

INTRODUCTION

- The demand for mobility has been strongly increasing over the past few years. As minimum intervals between two starting or landing planes are necessary for security reasons, evasion of air traffic to shoulder hours and even the nighttime has been observed in the past an will even increase in the future. Simultaneously, the strain of residents living in the vicinity of airports is likely to increase due to noise emitted from nocturnal air traffic.
- Environmental noise is a potential disruptor of the sleep process and may cause changes in the structure of sleep. These changes may diminish the restorative power of sleep.
- By dividing polysomnographic recordings into intervals of 30 seconds, human sleep can be classified in six distinct states: Awake, stages 1-4, and REM [1].
- The sleep states differ in their contribution to the restorative power of sleep. Stages 3 and 4 (slow wave sleep, SWS) and REM (rapid eye movement) sleep play an important role for the recuperative value of sleep. Research effort in the past was restricted to the prediction of noise induced awakenings.

OBJECTIVES

1. To build a Markov state transition model for the simulation of noise-free baseline nights (model 1)
2. To extend model 1 for the consideration of the influence of aircraft noise on transition probabilities depending on maximum sound pressure level $L_{AS,max}$ and the time pattern of aircraft noise events (ANEs)
3. To compare three different noise patterns with $L_{AS,max}$ 60 dB:
   (1) unrestricted nocturnal air traffic
   (2) as (1), but no air traffic between 11:00 p.m. and 5:00 a.m.
   (3) as (2), but traffic between 11:00 p.m. and 5:00 a.m. from (1) added to the two hours preceding and following the silent period

METHODS

- **Data Sources:** In four sleep laboratory studies with 112 subjects (74 female, aged 18-65) lasting from 1999 to 2003, the Institute of Aerospace Medicine of the German Aerospace Center (DLR) investigated the influence of aircraft noise on human sleep [2]. Data of more than 33,000 ANEs and related events were used to estimate transition probabilities between different sleep states as a function of the maximum sound pressure level of the ANE.
- **Statistical Analysis:** Transitional models based on multinomial autoregressive logistic regression [3] were build in a stepwise manner to simulate noise-free baseline nights. A linear term representing $L_{AS,max}$ of the ANE was then added to the model that produced the most valid results. It was assumed that ANEs influenced transition probabilities for no longer than 60 seconds.
- **Model Validation:** The following variables were used for baseline model validation: duration of ultradian sleep cycles, fractions of SWS, REM and awake in sleep cycle length, fractions of different sleep stages in total sleep time, number of sleep stage changes, time spent in each sleep stage without transition to different stages. Additionally, Markov traces produced by first-order MC simulations should resemble realistic human hypnograms.
- **Outcome:** Fractions of the different sleep stages in the sleep period time.

RESULTS

- A second-order Markov state transition model (i.e., transition probabilities depend on two previous states) turned out to satisfy the validation criteria best. The following terms were included in the final model: intercept, variables representing sleep stage 30 seconds (T_{-1}) and 60 seconds (T_{-2}) prior to transition (first and second order terms - 5 indicator variables each), 5 indicator variables C1-C5 representing the time spent in the same sleep stage (30, 60, 90, 120 and 150 seconds), interactions REM_T_{-1}* C1 and REM_T_{-1}* C2, cycle number after sleep onset (linear term).
- Sleep stage fractions in total sleep time: Comparison of mean values from baseline nights and 10,000 first-order MC trials showed excellent agreement (model versus observed data: Awake –0.7%, S1 +27.5%, S2 +0.5%, S3 +2.5%, S4 –8.8%, REM –1.5%).

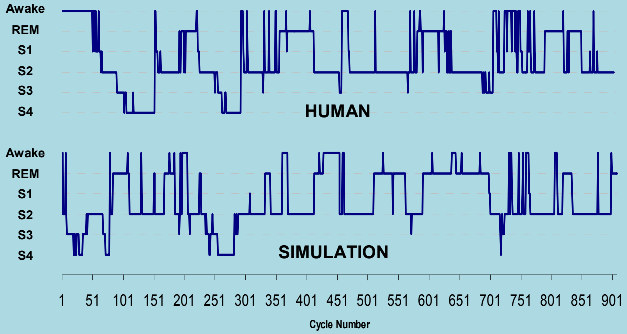
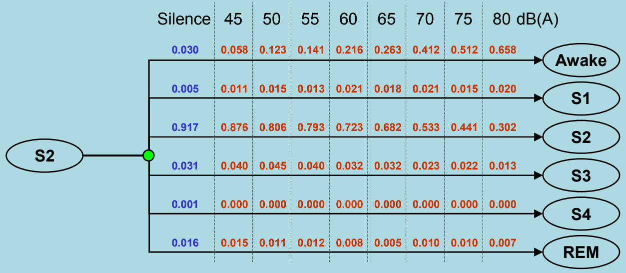


Figure 1: A typical human hypnogram compared to the Markov trace of a first-order MC-simulation (2nd-order autoregressive multinomial model). Typical features of human sleep are reproduced by the model.

- The model validly reproduces key features of human sleep, e.g. S3 & S4 predominantly occurring in the first half of the night (see *Figure 1*).
- Aircraft noise leads to a dose-response like change in transition probabilities. This is exemplified in *Figure 2* for sleep stage S2: The awakening probability increased while the propensity changing to deeper sleep stages simultaneously decreased under the influence of aircraft noise.
- Changes of the sleep stage fractions in total sleep time depending on the three different noise patterns (see OBJECTIVES) are shown in *Figure 3*. Noise restriction between 11 p.m. and 5 a.m. (pattern 2) reveals clear benefits compared to unrestricted traffic in terms of less time spent awake and more time spent in stages 3 and 4 and REM sleep. These benefits are reduced (but still present) when the traffic that formerly took place between 11 p.m. and 5 a.m. is redistributed before and after the silent period (pattern 3).



S2	Silence	45	50	55	60	65	70	75	80 dB(A)
Awake	0.030	0.058	0.123	0.141	0.216	0.263	0.412	0.512	0.658
S1	0.005	0.011	0.015	0.013	0.021	0.018	0.021	0.015	0.020
S2	0.917	0.876	0.806	0.793	0.723	0.682	0.533	0.441	0.302
S3	0.031	0.040	0.045	0.040	0.032	0.032	0.023	0.022	0.013
S4	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
REM	0.016	0.015	0.011	0.012	0.008	0.005	0.010	0.010	0.007

Figure 2: Noise induced changes in transition probabilities from sleep stage S2. Notice the dose-response like increase in awakening probability.

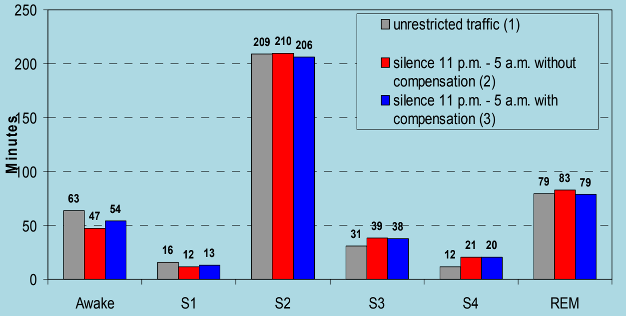


Figure 3: Comparison of sleep stage fractions for traffic patterns 1, 2 and 3.

LIMITATIONS

- The interaction of several successive ANEs as well as more complex countermeasures of the body in form of adaptation processes has not be taken into account.
- We used data based on sleep laboratory studies, which may not reflect the reality in the field.

CONCLUSIONS & RECOMMENDATIONS

- It was possible to validly reproduce key features of noise-free baseline nights with a Markov state transition model based on multinomial autoregressive logistic regression.
- The expansion of the model based on extensive data on the reactions to aircraft noise events allows for the comparison of the sleep structures induced by different noise patterns and may serve as a valuable tool for optimizing the structure of nocturnal air traffic and therefore may aid politicians in environmental decision making.

REFERENCES

(1) Rechtschaffen, A. et al.: A Manual of Standardized Terminology, Techniques and Scoring System for Sleep Stages of Human Subjects (1968) Washington, D.C., Public Health Service, U.S. Government, Printing Office
(2) Basner M. et al.: Aircraft Noise Effects Volume 1: Executive Summary (2004), DLR-FB-2004-07/E, www.dlr.de/flightphysiology
(3) de Vries S.O. et al.: Fitting Multistate Transition Models with Autoregressive Logistic Regression (1998) Med Decis Making (18): 52-60

Correspondence:

Mathias Basner, MD
Institute of Aerospace Medicine, German Aerospace Center (DLR)
Linder Hoehe, 51147 Cologne, Germany
Tel.: +49-2203-601-3058, Fax: +49-2203-68323
Email: mathias.basner@dlr.de