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HUMAN FATIGUE RISK SIMULATIONS IN 24/7 OPERATIONS

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ABSTRACT

A Circadian Alertness Simulator (CAS) is presented as an interactive tool for assessing sleep behavior and fatigue risk in 24/7 operations. The simulation model uses as input sleep-wake data and information about individual sleep characteristics (short vs. long sleeper, morning type vs. evening type, napper vs. non-napper). The validation of the CAS model was based on a figure of merit function reflecting the model's ability to minimize the difference between reported and predicted sleep data. The purpose of the alertness model is the assessment of work schedules in terms of fatigue risk.

1 INTRODUCTION

Simulation models are becoming one of the most important tools for analyzing and solving complex problems in engineering, science and many other areas such as manufacturing, logistics, transportation, military operations, scheduling, computer systems, networking, etc. (Banks 1998). The recent advances in simulation software programs are impressive. Despite all this progress, simulation tools which model human behavior are relatively rare. One important area of human factors research is the impact of 24/7 operations on the fatigue state of employees. Acute and cumulative fatigue has become an increasing problem in our 24/7 world. Economic pressures and globalization trends have led to increasing numbers of people having to work non-traditional and/or long hours.

Circadian Technologies, Inc. has developed a Circadian Alertness Simulation (CAS) model that allows the assessment of fatigue risk based on sleep-wake patterns. Since the model includes an algorithm that predicts the most likely sleep pattern given a specific work pattern, the model allows us to rank proposed shift schedules for fatigue-related risk before implementing these schedules. The impact of different shift schedule options on the alertness level and the resulting fatigue risks of an individual employee are relatively uncertain and difficult to calculate analytically, especially if the individual sleep characteristics of the employee is not known. Here, the application of a simulation tool is particularly useful. Simulation models help us understand when situations of extreme fatigue risk occur and why. Another important application of the alertness simulation model is accident investigation. Based on multiple simulations, the probability of fatigue as an accident factor can be predicted.

This paper describes how the CAS model was developed, how the model parameters can be adjusted with the goal to improve the match between reported and predicted sleep patterns, how the model was validated and how the Circadian Alertness Simulator can be applied to address the two special problems described above.

2 CAS – MODEL CONCEPT

The CAS concept is based on the Two-Process Model of sleep regulation (Daan et al. 1984). A homeostatic component and a circadian component are combined to calculate an alertness curve. Figure 1 shows the interaction between activity data (horizontal bars), the circadian component and homeostatic components, resulting in an alertness score. Alertness at any certain point in time is entirely a function of all preceding data points. It therefore includes effects of acute and cumulative fatigue.

Based on the calculation of alertness, it is also possible to predict a sleep/wake pattern by triggering sleep when alertness reaches a certain lower threshold. The algorithm assumes sleep and calculates the subsequent data points assuming sleep until an upper wake-up threshold or an activity block (e.g., work, commuting) is reached. This capability was used for the model validation and it allows the analysis of data where there is no information about the

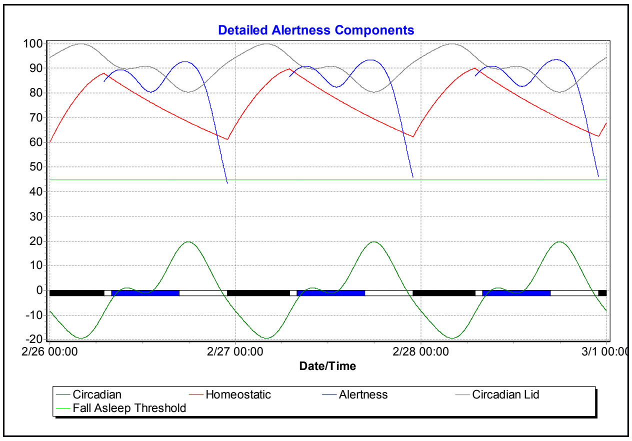

Figure 1: Components of the Two-process Model of Sleep Regulation and Sleep Prediction Algorithm for Three Consecutive Days.

person's actual sleep pattern (e.g. driver logs, time and attendance data, proposed work schedules).

In default mode, the CAS software simulates sleep and alertness for an average transportation employee, however, the model settings can be adjusted to simulate data for specific individual characteristics such as chronotype (morningness/eveningness), habitual wakeup time and napping capability.

The horizontal bars in Figure 1 indicate the activity of the person (black=sleep; white=awake; blue=duty). The circadian component (dark green), the homeostatic component (red line) and the alertness curve are shown together with the circadian lid (wake-up threshold) and fall-asleep threshold for the sleep prediction algorithm.

The model allows prediction of the most likely sleep pattern around a given work pattern. The sleep pattern is then used to estimate the fatigue impact of the sleep-wake-work pattern.

The simulation of human alertness and sleep behavior has many benefits. It allows the user to evaluate the fatigue risk of existing work assignments and the consequences of work schedule interventions before their implementation in the real world.

3 CAS – MODEL VALIDATION

The underlying model parameters can be adjusted to different values in order to tailor CAS to different applications. For the current transportation version, the free parameters of the model were iteratively adjusted in order to best fit an experimental database of 109 railroad engineers. Each individual reported 30 days of sleep-wake-work pattern. This group provided a total of 3,684,258 minutes for sleep simulation (not counting periods when the algorithm prohibited sleep due to work or commuting activity within the prior or subsequent 60 minutes). For these minutes, the match between actual and predicted sleep was measured. A "figure of merit function" was calculated to quantify the agreement between observed and predicted sleep episodes. We arranged the "merit function" as a weighted combination of the Root Means Square Error and a Correlation function (Gilchrist 1976), so that small values represent a close agreement ("good fit"). The user can select the weight of each of the two individual criteria. The model parameters were adjusted to achieve a minimum in the merit function by means of a multidimensional Simplex Optimization Method.

The validation of the CAS model was based on the comparison of actual and simulated sleep patterns of single people and/or groups of people with work pattern information.

Figure 2 shows the actual and predicted sleep patterns for an individual. The data is shown as double plot. Each horizontal sequence of colored bars represents 48 consecutive hours. Both charts show the same 31-day period of the same individual. The black bars indicate sleep episodes. The example shows the sleep-wake-work pattern for a train engineer with the originally reported sleep (left chart) and the predicted sleep (right chart). The agreement between the black bars in both graphs was calculated and used as the criterion for the model validation.

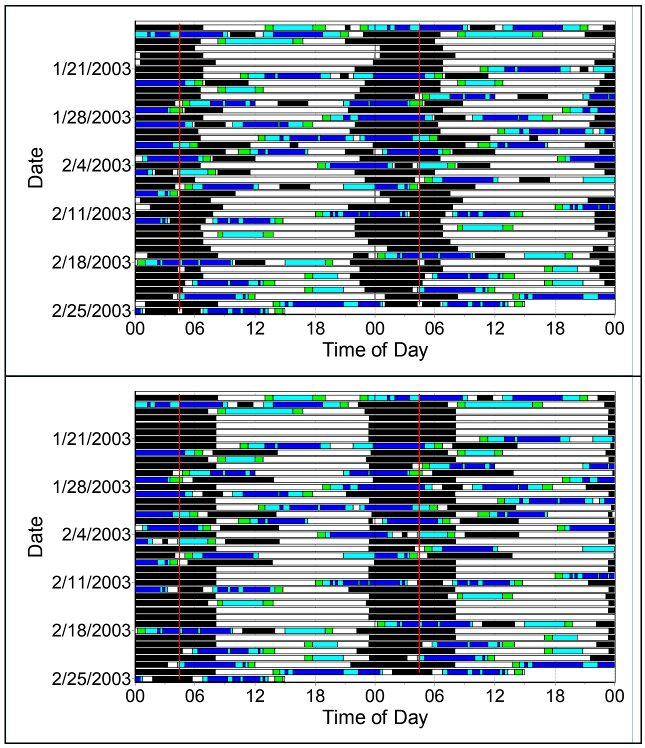

Figure 2: Original Sleep (top) and Predicted Sleep (bottom) for a 31-day Period of a Freight Train Engineer (Colors: black=sleep; white=awake; green=commute; blue=duty).

The train engineer data was chosen for the initial validation because this population presents a special, less complex case. Working irregular and unpredictable work schedules, train engineers sleep mainly at night as opposed to shiftworker populations on regular rotating work schedules. Therefore, shifting of their circadian phase is minimal in train drivers and could be neglected in the simulations. However, the model does have the capability to simulate phase shifting. This algorithm component can be activated depending on the problem to be simulated.

4 MODEL APPLICATION AS A TEACHING TOOL

The model can be used for the demonstration of the effects of circadian rhythms and sleep patterns and the impact of alterations to existing sleep-wake-work patterns.

In the example in Figure 3, a 45-minute nap was inserted at 12:30 (middle panel) and at 18:00 (bottom panel) to demonstrate the importance of the right timing of the nap for a partially sleep-deprived subject. At 12:30 the gained alertness is larger than at 18:00, since the evening peak in alertness places the individual already at a relatively alert state. By using the early afternoon dip for the nap, the effect can be increased.

5 MODEL APPLICATION FOR DETAILED RISK ANALYSIS

Another way to use the model capabilities is to simulate alertness of an individual as a function of time based on simulated/actual sleep patterns. In addition, the overall fatiguing impact of a given sleep-wake-work pattern can be assessed.

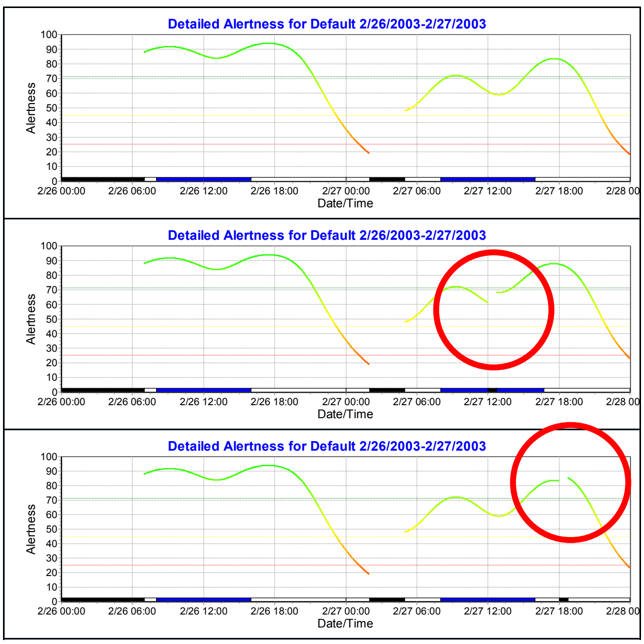

Figure 3: Impact of Naps at Different Times of Day on the Calculated Alertness.

Figure 4 shows an alertness curve for two consecutive days. The type of activity at any time is shown as colored horizontal bar below the curve (black=sleep; white=awake; green=commute; blue=on-duty).

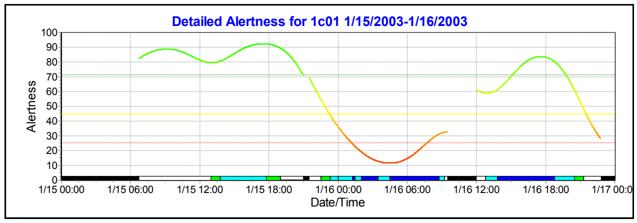

Figure 4: Alertness Curve as a Function of Time.

In this mode, it is possible to identify specific times with low alertness and high risk. In this example, the individual worked through the night without sufficient sleep before his/her night work assignment. This leads to dangerously low alertness during the early morning hours of the work assignment.

The distribution of the alertness value during a certain activity can provide additional information. The chart shown in Figure 5 is this different way of looking at the alertness curve data. The chart shows the frequency with which certain alertness values occur during a specific activity. In the example, only the activities commuting (green), prep-work (light blue) and operating the train (dark blue) are included in the chart. The chart shows the frequency of times when the individual was operating a train or commuting at very low alertness levels. The simulation tool allows the user to answer various questions such as: 'How would alertness improve if the individual had slept for more than 5 hours?' 'What is the optimal sleep timing before going to work?' 'Why is sleep at certain times of the day more beneficial?' The CAS model can simulate any assumptions regarding possible sequences of work, wake and sleep with the goal to minimize the risk of fatigue.

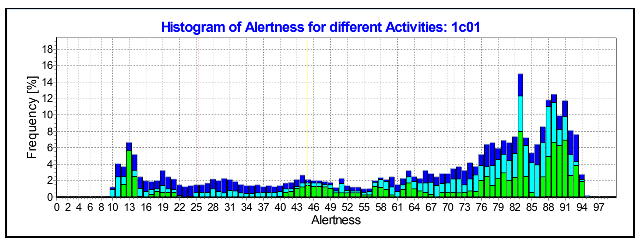

Figure 5: Frequency Distribution of Simulated Alertness During Work and Commute Activities (blue = work; green = commute).

6 MODEL APPLICATION FOR RISK ANALYSIS WITH UNCERTAINTY

An especially important application of the CAS model is its use in situations where there is a degree of uncertainty about the individual sleep characteristics and sleep-wake history. One typical example is the investigation of the role of fatigue in severe accidents. In this mode of operation, the CAS model simulates alertness levels with varying individual properties and sleep-wake pattern inside the established limits of the accident investigation. The result of this simulation is an uncertainty range of possible alertness values and the most likely alertness at any given time (Figure 6).

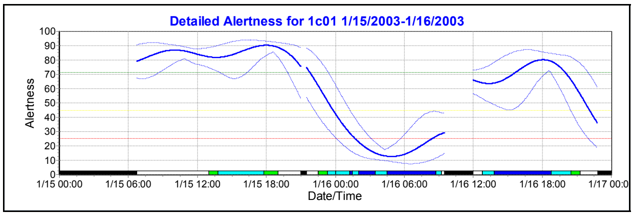

Figure 6: Range of Alertness as a Function of Varying Individual Profile Settings.

As seen in Figure 6, the alertness curve output changes from one specific number to an upper limit, a lower limit and a mean at any given time. Especially in accident analysis, this information about the uncertainty range for the simulated alertness is very useful and gives a probability score about the possible fatigue cause for the accident.

7 MODEL APPLICATION FOR GROUP ANALYSIS

Another important application for the CAS model is the simulation of large groups of employees. In this mode, the employer provides the time-and-attendance data and the model applies the sleep prediction algorithm. Predicting the sleep pattern for each individual, the model can then assess the fatigue impact of the work patterns in the group. This impact can be expressed as a single number in the model's cumulative Fatigue Risk Score. This score is a number between 0 and 100, where lower numbers indicate low fatigue and high numbers high fatigue.

Based on the simulated alertness outcome of 430 individual work patterns of a trucking company, the system assessed the fatigue risk of the work patterns. The distribution of these cumulative Fatigue Risk Scores is shown in Figure 7. Simple changes in the work patterns have positive or negative consequences on the Fatigue Risk Score. The obtained feedback from the CAS models allowed the managers of the trucking company to modify the work schedule accordingly (Moore-Ede et al. 2003).

In addition to the Fatigue Risk Score distributions resulting from varying individual work patterns in a given operation, Fatigue Risk Score distributions can be also computed for one given work pattern (e.g. a proposed shift schedule). A group can also represent the range of individual sleep characteristics in the population that might work one proposed schedule. In this case the outcome would be a fatigue distribution describing how the whole group will be affected by the proposed work schedule – therefore showing the effect of one schedule on different individuals.

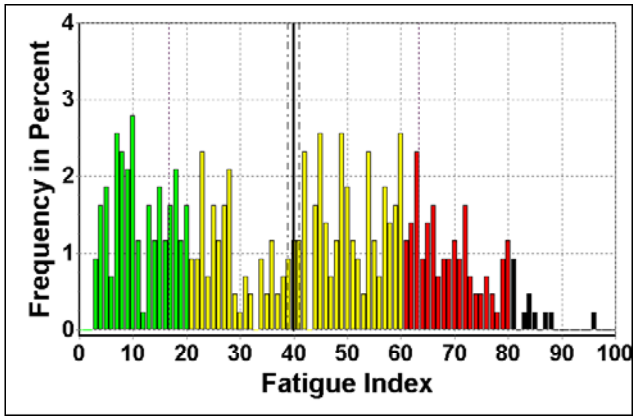

Figure 7: Distribution of Cumulative Fatigue Risk Scores in a Group of 430 Individuals of a Trucking Operation.

8 CONCLUSION

The CAS model described here has been applied in real world scenarios and proven to be a valuable source of information for managers in charge of the work schedules of their employees. With this system, the manager can identify problems and react before these problems make themselves visible through accidents or errors. The CAS system allows simulation of the fatigue impact of proposed work schedules before they are implemented, or the analysis of historical work data with or without information on sleep patterns. The CAS model can also be used for accident analysis or educational/training purposes.

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MARTIN MOORE-EDE is Chairman and CEO of Circadian Technologies, Inc. a research and consulting firm focusing on the optimization of employee work schedules in extended hours (shiftwork) operations, and reducing the costs, risks and liabilities of the 24/7 workforce. As a Professor of Physiology at Harvard Medical School he was a pioneer in defining the regulation of circadian sleep-wake cycles by circadian pacemakers (biological clocks). He has published 10 books and 135 scientific articles on the application of human physiology to the optimization of work in the 24/7 economy.