FATIGUE MODELING AS A TOOL FOR MANAGING FATIGUE IN TRANSPORTATION OPERATIONS

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LIST OF FIGURES

PURPOSE

The purpose of the ***FAST*** development effort has been to develop a user-friendly, computerized tool for operational planners and schedulers based on a highly researched and recognized model of human sleep and cognitive performance. The Fatigue Avoidance Scheduling Tool (***FAST***) allows a user to predict cognitive performance efficiency based on the timing and amount of sleep an individual receives prior to and during the period. For transportation applications, ***FAST*** provides the scheduler the ability to assess fatigue consequences of alternative schedules.

SUMMARY OF FATIGUE MANAGEMENT SOFTWARE

The effort has built on a newly developed model of sleep and performance invented by the first author called the Sleep, Activity, Fatigue, and Task Effectiveness (**SAFTE**) Model [1]. This model predicts human cognitive performance based on 20 years of sleep and circadian rhythm research. Hursh invented the first sleep and performance model for the Walter Reed Army Institute of Research and the current model is an advanced modification of that Army model. The current version of the model makes valid predictions of performance under a broad range of schedule conditions, from minimal to complete sleep deprivation, at any time of day and for normal adult subjects ranging in age from the early twenties to mid-fifties. The model is homeostatic and adjusts its predictions of future performance based on the recent sleep history of the projected population or specific individuals. In the model, a circadian process influences both performance and sleep regulation. Sleep regulation is dependent on hours of sleep, hours of wakefulness, current sleep debt, the circadian process and sleep fragmentation (awakenings during a period of sleep) that reduce sleep quality. Performance is dependent on the current balance of the sleep regulation process, the circadian process, and sleep inertia. An additional benefit of **SAFTE** is that it can be easily enhanced by future studies to refine fatigue effects on specific subject populations, specific aspects of operator performance, and the effects of interventions.

The initial phase of the ***FAST*** development effort incorporated the **SAFTE** Model into a software tool for scheduling operators to evaluate alternative schedules for their effects on performance capacity, as degraded by fatigue and circadian variation. The tool incorporates interpretive tools for visualizing performance changes over time and the capability to simultaneously compare multiple schedules on the basis of predicted changes in cognitive capacity. ***FAST*** allows the user to view the effects of pre-programmed and user-defined sleep/wake schedules on predicted performance effectiveness. The tool provides a simple, user interface enabling rapid visual and quantitative estimates of the effects of a variety of factors on the cognitive performance of operators. Figure 1 shows an actual screen from the current ***FAST*** program comparing two schedules simultaneously. Schedules may be viewed in a window, and two or more windows may be overlaid or tiled for comparison. They may be copied to another program or directly printed. The tool allows the user to load pre-programmed sleep schedules, edit them using keyboard and mouse commands, and save edited schedules.

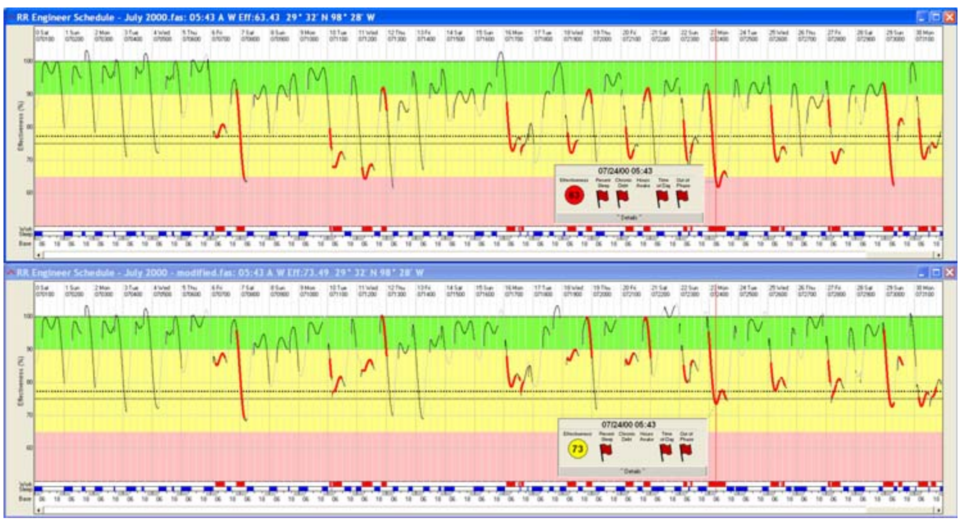

Figure 1: This is a screen image of the FAST main window and shows performance by a railroad engineer based on a log of sleep and on-duty time. The top window shows predicted performance based on actual sleep. The bottom window shows potential improved performance based on the addition of increased sleep during off-duty periods. The dashboard window shows a ten percent improvement in predicted performance effectiveness at the day and time indicated by the vertical cursor.

Effectiveness, as predicted by the **SAFTE** model, is displayed for a user-selectable interval ranging from 6 hours to over 30 days. The program allows simultaneous editing and comparison of any number of work and sleep schedules. A standard Windows menu structure has been implemented, along with export to other programs, such as a spreadsheet or presentation.

Several options have been developed to aid the interpretation of performance changes. One valuable option to aid comparison of several schedules is the overlay of a table of interval statistics. This table shows the average "Performance Effectiveness" for successive hours while awake and while working. In addition to average effectiveness, the program computes the percent of time below a selectable criterion, such as 70% effectiveness. The percent of time below criterion (% BCL) gives an estimate of the time spent at higher risk of error. These tables can be printed or copied to the clipboard for inclusion in other documents.

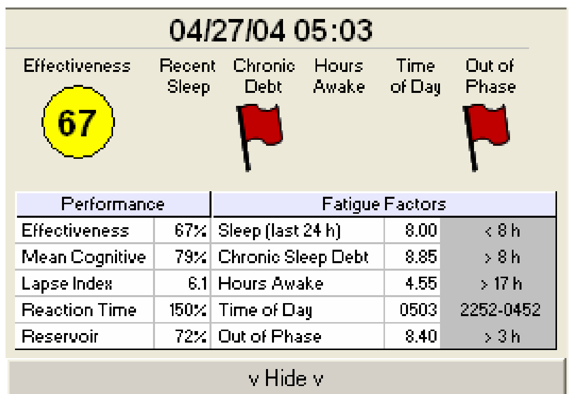

*Figure 2: This is a screen shot of the dashboard display with **FAST** showing the levels of five fatigue factors and five performance metrics. At this time in the schedule (0503 hrs), two fatigue factors are at dangerous levels (red flags).*

A second valuable tool is the fatigue indicators dashboard shown in figure 2. This window provides a summary of critical fatigue factors operating at any time in a schedule. The user can place the cursor at any time in the schedule using the graphical screen and the dashboard will summarize five fatigue factors and indicate if any factors are at a potentially dangerous level. The fatigue factors are: amount of sleep in the last 24hrs, chronic sleep debt, number of hours awake, time of day, and circadian phase desynchrony. The dashboard also displays alternative performance metrics such as lapse likelihood and reaction time changes. The dashboard feature was specifically added to the ***FAST*** software to aid with the analysis of factors that might contribute to an operator error or accident. Whenever effectiveness declines below approximately 90%, the dashboard can be consulted for factors that are responsible for that decline in performance. This helps to explain the deficit and points to potential strategies to correct the problem.

SAIC has created an algorithm for shift-work phase adjustment and transmeridian relocation within the **SAFTE** model. The model contains logic to detect the change in work/sleep patterns and to readjust the phase of the circadian rhythm depending on whether the new pattern is indicative of a change in time zone or shift in work schedule (shift rotations). The phase adjustment feature permits the circadian process to predict "Jet Lag" based on travel from east to west and west to east, illustrated in Figure 3. This feature also permits the software to properly adjust the circadian rhythm for shift-work schedules typical of many transportation and industrial operations.

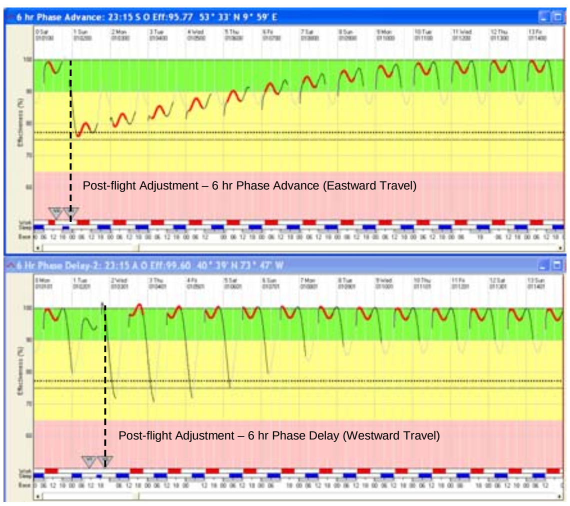

Figure 3: Disruptions of performance following eastward (upper pane)l and westward (lower panel) travel across 6 time zones. Note that the model predicts greater on the job disruptions (red portion of line) following eastward travel and a longer period of adjustment.

For aviation applications, the software can display waypoints along the travel route. The program computes lighting conditions and approximate interpolated geographic positions. The user can print a Mission Timeline to guide the crew during the performance of the flight.

Transportation Specific Features

An initial version ***FAST*** was used to validate the use of in-flight naps to maintain performance of Air Force bomber crews conducting 30 and 45 hr missions and to guide the design of night training exercises. In 2002, the Army, Air Force, and Navy convened a meeting to discuss fatigue modeling and the **SAFTE** Model was accepted as the base model for continued DOD development. Other organizations have also expressed an interest in using ***FAST***. The Federal Railroad Administration is using the tool to assess fatigue as a possible contributing factor to major rail accidents and the FAA and NTSB are monitoring progress in the development effort for potential applications for schedule assessment and accident investigations. The Federal Railroad Administration has initiated a program to validate and calibrate the tool for fatigue management and accident investigation in rail operations. The program has lead to the development of specialized components for ***FAST*** that incorporate all the earlier features of ***FAST*** plus the ability to compute likely sleep patterns based on a work schedule, an algorithm called **AutoSleep**. This algorithm is critical for application of any fatigue model in transportation because managers only know the work schedules of workers and opportunities to sleep, not actual sleep times. The AutoSleep algorithm is based on a study of railroad engineer work and sleep logs collected from about 150 engineers conducted by Pollard [2]. Based on the average sleep habits of subjects in that study, the AutoSleep algorithm creates a reasonable pattern of sleep based on several decision criteria: normal bedtime, normal length of work day and rest day sleep, average commute time, and time reserved for personal or family activities (forbidden zone). The sleep generator using the default settings emulates the average sleep patterns of someone working under an irregular work shift schedule. For incident investigations, the algorithm can be set to emulate the particular sleep habits of the person involved in the incident.

THE SAFTE MODEL

The general architecture of the current **SAFTE** model is shown in Figure 4. A circadian process influences both performance and sleep regulation. Sleep regulation is dependent on hours of sleep, hours of wakefulness, current sleep debt, the circadian process, and fragmentation (awakenings during a period of sleep). Performance is dependent on the current balance of the sleep regulation process, the circadian process, and sleep inertia. Although developed independently, the resulting model has structural similarity to the scheme suggested by Acherman and Borbely [3] and when the simulation is integrated over time approximates (ignoring circadian influences in the model) the mathematics of the homeostatic model of Folkard and Akerstedt [4]. However, the new model has been optimized to predict changes in cognitive performance and incorporates features not included in any prior comprehensive model. These features are: a multi-oscillator circadian process, a circadian sleep propensity process, a sleep fragmentation process, and a circadian phase adjusting feature for time zone changes. Each component will be discussed in detail.

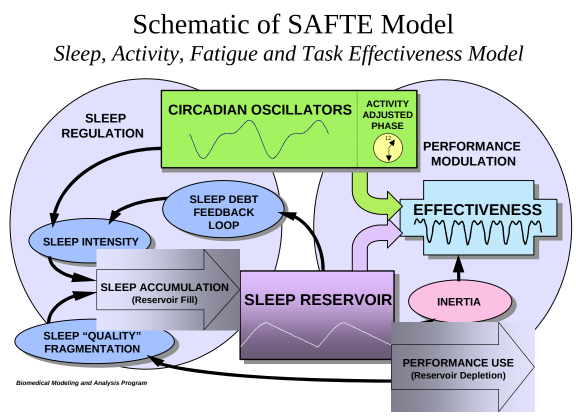

Figure 4: Block diagram of SAFTE Model, Version 2.

Components of the Model

Circadian Oscillators

Performance while awake and the drive to sleep are both controlled, in part, by a circadian process [4], [5]. Performance and alertness reach a major peak in the early evening, about 2000 hours, and fall to a minimum at about 0400 hours. There is a secondary minimum in the early afternoon, about 1400 hours, and a secondary morning peak at about 1000 hours. Correlated with this pattern is a rising tendency to fall asleep that reaches a peak at about the same time performance and alertness reach their minima. The existence of both a major and a minor peak in performance and two corresponding minima at other times suggests that at least two oscillators are involved in the circadian process.

The sleep and performance model incorporates a circadian process that is composed of the sum of two cosine waves, one with a period of 24 hours and one with a period of 12 hours. This arousal oscillator drives both variations in predicted cognitive effectiveness and sleep propensity. These two translations of the oscillator have identical frequency and phase components and differ only in amplitude and sign; a rise in arousal produces an increase in performance and a decrease in propensity to sleep. The circadian process is depicted in the large rectangle shown in the diagram of the **SAFTE** model, Figure 4. In addition, based on observations that the amplitude of circadian variation increased with hours of sleep deprivation, the amplitude of the performance rhythm is a linear function that increases from a minimum to a maximum depending on the level of sleep debt (reservoir capacity minus current reservoir level).

Activity Adjusted Circadian Phase

When subjects move to another time zone or alter work patterns so that sleep and work occur at different times of day, the internal circadian oscillator that controls body temperature and alertness shifts to this new schedule. During the period of adjustment, subjects experience performance degradation, disrupted mood and feelings of dysphoria, called circadian desynchronization or "jet lag" [6], [7], [8]. The model mimics this process and automatically adjusts the phase of the circadian rhythm to coincide with the activity pattern of the subject. This feature is critical for the accurate prediction of the effects of moving to a new time zone or changing to a new and regular work pattern, such as changing from the day shift to the night shift. When ones moves to a new work schedule or a new time zone, the change in average awake time (relative to a reference time zone) is detected and a new "target phase" is computed. The model adjusts to the new "target phase" gradually over the course of many days. During that time, the performance of the subject will show degradation due to the desynchronization of the internal circadian rhythm from the new rhythm of work and sleep. The rate of adjustment is slower for phase advances (eastward travel) compared to a phase delay (westward travel; see Klein and Wegman, 1980; Haus and Halberg, 1980). When coupled with light information computed by the FAST software, the phase adjustment algorithm also can differentiate shift work from transmeridian travel and adjust the circadian phase more gradually, as appropriate for shift work.

The Sleep Reservoir and Homeostatic Sleep Regulation

The control of sleep and its influence on cognitive capacity is a homeostatic process (see [9], [10]). At the core of this process is a sleep reservoir, diagrammed as a rectangle at the center of the diagram in Figure 4. The model simulates the underlying processes that govern the capacity to perform. A fully rested person has a certain performance capacity. While awake, units of this reservoir are depleted each minute according to a linear performance use function, indicated by the arrow leaving the reservoir. While asleep, units of capacity are added to the reservoir each minute to replenish the reservoir and the capacity to perform and be alert. The rate of accumulation for each minute of sleep is called sleep intensity and is driven by two factors: 1) the circadian variation in sleep propensity, and 2) the current reservoir deficit compared to the reservoir capacity. This deficit is constantly changing as one sleeps and replenishes the reservoir, or is awake and depleting the reservoir. The oscillation in the reservoir level is called the sleep-wake cycle. Note that sleep accumulation does not start immediately upon retiring to sleep. Following an awakening there is a minimal delay of about 5 min required to achieve a restful sleep state. This factor accounts for the penalty during recuperation that is caused by sleep in an environment that leads to frequent interruptions (sleep fragmentation) and as a result of a sleep disorder such as sleep apnea. These components of the sleep accumulation function are indicated as ellipses in the diagram (Figure 4) to the left of the sleep reservoir feeding into the sleep accumulation function. A schedule can oscillate between sleep and wake states as often as once a minute and the simulation will keep account of the net effects on performance capacity as the balance in the reservoir, like the balance in a check book.

Cognitive Effectiveness

Consistent with the approach proposed by [5] and [3], the **SAFTE** model stipulates that cognitive effectiveness and alertness are primarily dependent on variations in the two processes just described: the endogenous circadian rhythm (reflected in body temperature) and current sleep reservoir balance resulting from the sleep-wake cycle. A third factor, called sleep inertia, is the temporary disturbance in performance that often occurs immediately following awakening, see [10]. The predictions of the model are normally in terms of changes from cognitive effectiveness, expressed as percent of baseline performance when well rested. This measure corresponds to performance on a psychomotor vigilance task. In addition, the parameters of the performance calculation can be adjusted to predict other components of performance, such as cognitive throughput, reaction time, and lapses in attention.

Predictions of the Model

Performance and Alertness

The average person is assumed to require eight hours of sleep per day to be fully effective and to avoid accumulation of sleep debt. Based on the joint interaction of the endogenous circadian oscillator and the sleep-wake cycle, performance is predicted to have two peaks in percent effectiveness at approximately 1000 hours and 2000 hours, a minor dip in performance at about 1400 hours, and a major trough in effectiveness during the early morning hours when the person is normally asleep. This pattern is shown in Figure 5. The nighttime pattern reveals a major trough in performance in the early morning hours, which corresponds with the average alertness scores shift workers studied around the clock without accumulated sleep debt [12].

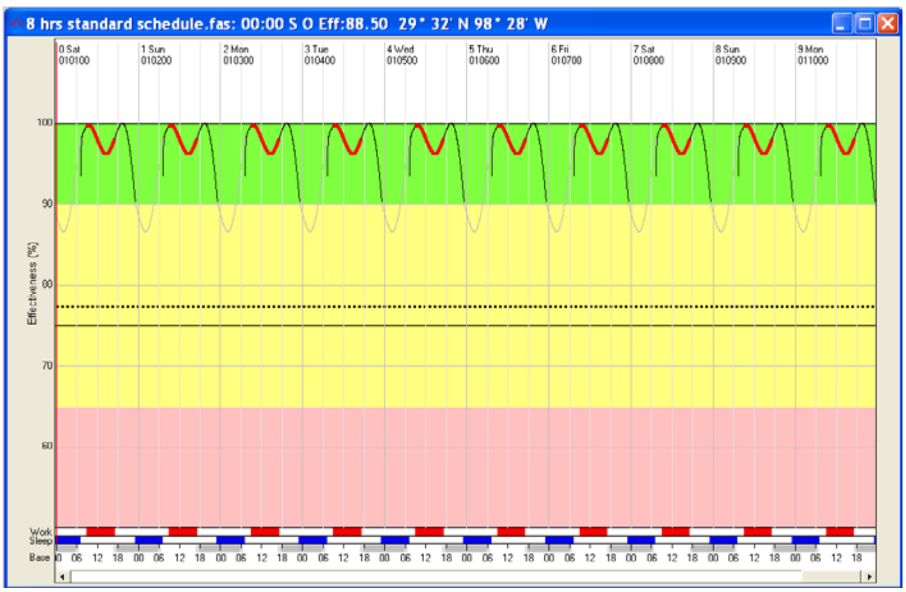

Figure 5: Predicted cognitive effect as a function of time of day. Cognitive effectiveness is plotted in percent as a function of time on the x-axis, shown in days and hours. Work intervals are in red and sleep intervals are in blue. The graph shows a minor dip in performance in the afternoon and a major nadir in performance in the early morning (see text).

A number of studies have confirmed the bimodal pattern of performance shown in Figures 5. Lavie [13] reported that traffic accidents in Israel between 1984 and 1989 reveal two peaks in sleep related accidents, a major peak at about 0300 hours, and a minor peak at about 1500 hours in the afternoon. Similarly, Voigt, et al., [14] report acoustical reaction time as a function of time of day and, again, there are two peaks (slowing) of reaction time, a major one at about 0200 hours and a minor one at about 1400 hours. Finally, Folkard and Monk [15] summarized results from industrial settings showing two dips in performance, one at about 0300 hours and a second at about 1400 hours.

Sleep Propensity and Sleep Intensity

The intensity of sleep is the sum of two processes, as well [13]. As described earlier, the circadian process produces an oscillation in sleep propensity. This rhythm is the negative of the arousal rhythm and scaled in sleep units. Sleep propensity combines with the current sleep debt resulting from the sleep-wake cycle to generate a prediction of *sleep intensity*. For a person taking a normal 8 hours sleep from midnight to 0800 hours, sleep is most intense in the early morning at about 0300 hours. There is a mid-afternoon increase in sleep propensity at about 1600 hours that coincides with the mid-afternoon dip in alertness and consistent with the observation of increases in sleep related traffic accidents [13].

Equilibrium States

A homeostatic representation of sleep regulation leads to an important implication: if a subject is scheduled to take less than an optimal amount of sleep each night, for example, four hours per day, the reservoir initially loses more units during the awake period than are made up during the sleep period. This results in a sleep debt at the end of the sleep period that accumulates over days. However, since the rate of sleep accumulation increases with sleep debt, eventually, the rate of sleep accumulation increases such that four hours of sleep makes up for twenty hours awake. At this point, the reservoir reaches an equilibrium state and no further debt is accumulated, although the initial deficit remains as long as the person remains on this schedule. The sleep homeostat is not infinitely elastic; any schedule that provides less than 4 hours of sleep per day (for the average person) will not reach an equilibrium state and performance capacity will gradually deplete to zero.

Sleep Timing

The model is sensitive to the time of day of the sleep period. For an individual given eight hours of sleep per day, starting at 1200 hours (noon) each day, performance reaches a peak of 100 % at the start of each awake period (2000 hours); performance then rapidly declines during the late night and early morning hours to a strong dip at about 0400 hours. Minimum predicted performance could be as low as 66% compared to minimum performance under a normal sleep schedule of 90%. This alteration in pattern results from two factors. First, sleep intensity is initially less for sleep periods starting at noon. This results in a small accumulated debt that is quickly offset by the homeostatic sleep mechanism. The second, more persistent effect is the circadian oscillation of performance that reaches its minimum in the early morning hours. This pattern has strong implications for performance under shift schedules that require daytime sleep. It is well documented that most mistakes on the night shift occur during the early morning hours ([16], [17], and [18]).

Validation of the SAFTE Model

The **SAFTE** model incorporates a number of improvements compared to the prior models. In general, those changes discussed above were designed to improve conformance with the underlying principles that form the basis of performance predictions. As discussed above, the model includes a realistic representation of the underlying circadian processes, a sophisticated routine governing the intensity of sleep as a function of time of day, and includes consideration of sleep inertia. To validate the model, the predictions of the model for the effects of total sleep deprivation were compared to an independent set of data reported by Angus and Heslegrave [19]. Their average results on a set of cognitive testes were plotted against the predictions of the **SAFTE** model with all parameters within the model set to the default values and the acrophase (peak of the 24-hr circadian rhythm) set to 1900 hrs and bedtime set to 2300 hrs. The model predictions for the actual data were exceptionally good with an R^2 of 0.98.

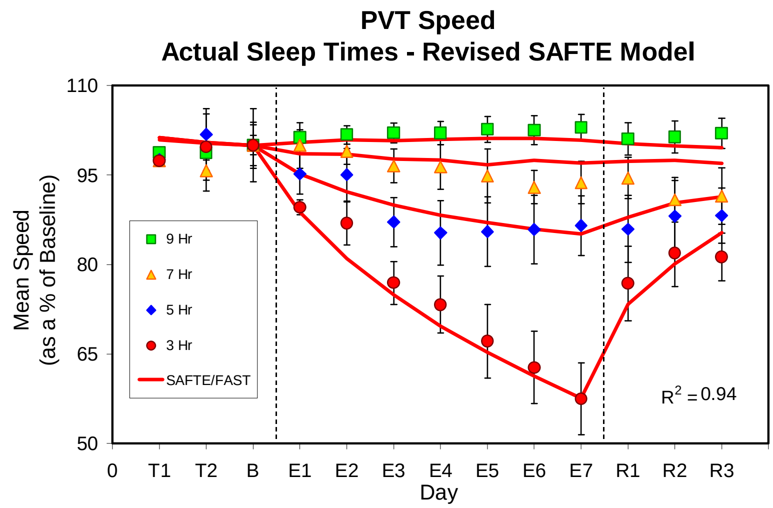

Figure 6: Fit of the current SAFTE model to the PVT results of the sleep dose response study based on actual sleep durations (Balkin, et al., 2000).

Often demanding civilian schedules provide less than the optimal eight hours of sleep a day for extended periods of time. These schedules provided chronic restricted amounts of sleep. A recent study of chronic sleep restriction conducted at the Walter Reed Army Institute of Research in cooperation with the Department of Transportation provided data on schedules of seven, five, and three hours of time in bed over seven days [20]. The latest version of the **SAFTE** Model predicts both the performance degradation effects and rate of recovery from those schedules with an R^2 of 0.94. The data are shown as symbols in Figure 6 and the predictions of the model are shown as the heavy lines. The first three points were from baseline days with eight hours time in bed; the next seven points were from the experimental days with time in bed set to the values shown in the legend; the last three days were with recovery sleep of eight hours time in bed.

One important outcome of this study was a quantification of individual variability in sensitivity to sleep restriction. Based on that finding, ***FAST*** can plot a line that represents some lower bound of the population variance, such as the lowest 20% of subjects. ***FAST*** may be the only fatigue model that estimates prediction error based on population variance.

PREDICTIVE VALIDITY AND CALIBRATION OF A FATIGUE MODEL FOR TRANSPORTATION APPLICATIONS

The FAST tool is currently being used to analyze work histories prior to railroad accidents to determine if some portion of those accidents is associated with low levels of predicted effectiveness based on work schedule and associated sleep opportunities. Approximately one third of accidents have been attributed to human factors related errors. Some undetermined percent of those accidents are probably due to inattentiveness or poor judgment resulting from inadequate sleep and/or time of day effects. The Federal Railroad Administration has undertaken a long term study to determine if a fatigue model, such as the **SAFTE/*FAST*** system, can predict a portion of human factors accidents based on an analysis of the work schedules alone. The first phase of this study was a pilot study of fifty accidents, approximately half caused by a human factors error. Each accident involved two crew members, so there were approximately 100 crew members involved in these fifty accidents. For each crew member, a 30-day work history prior to the accident was analyzed using ***FAST***. The model determined a plausible sleep pattern based on the sleep opportunities afforded by the work schedule. The model then determined projected effectiveness levels for every 30 min interval while at work throughout the 30-day work history. The model also determined the projected effectiveness at the time of the accident. Based on the work history, we determined the pattern of effectiveness levels during time spent at work. In general, the majority of time spent at work was with effectiveness levels above about 85%; about 6% of the time at work was with effectiveness below 65%. The analysis of the accidents indicated that the majority of accidents occurred with effectiveness above 85% when fatigue was likely not a factor. However, over 15% of the human factors accidents occurred with effectiveness below 65% - more than double the rate that might be expected based on a random distribution of accidents (6%). This suggests – without adequate statistical confidence because of the small sample size – that human factors accidents are elevated when predicted effectiveness is low, implicating fatigue (limited sleep opportunities and time of day) as a contributing factor in some human factors accidents and confirming the predictive validity of ***FAST***.

The Federal Railroad Administration is seeking data to expand this analysis with a much larger sampling of accidents to determine if this suggested relationship can be verified. A pool of 700 human factors accidents and a similar size sample of nonhuman factors accidents will be analyzed, as well as a similar sample of non-alcohol or drug related engineer decertification events. This large sample of about 2100 accidents and events should provide sufficient statistical power to 1) verify if a fatigue model based solely on work schedule data can detect a tendency for human factors accidents to occur with a higher likelihood when performance is predicted to be low (predictive validation), and 2) determine at what level of performance this tendency occurs (calibration).

ENHANCEMENTS OF *FAST* FOR TRANSPORTATION APPLICATIONS

Parallel with studies to validate and calibrate a fatigue model, efforts are underway to increase the ease with which such a tool might be used by industry. There are three initiatives underway:

1. Standard schedule file format for scheduling software.
2. Schedule design wizards for irregular work and regular shift work.
3. PC-based Fatigue Questionnaire for Accident Investigations.

The first initiative seeks to provide a standard file structure for representing work schedules that can be used by any scheduling software or fatigue analysis tool. SAIC (with NTI) has developed the ***FAST*** fatigue analysis system and uses a proprietary file format for schedule information. Another DOT funded software package for schedule design developed by XIMES analyzes shift schedules and work pools to determine the most efficient rotating schedule to meet work demands and personnel available. The program outputs a schedule file also that uses its own proprietary design. This initiative will result in a standard file format that can be used by any fatigue model or scheduling software and will provide for interoperability between packages.

The second initiative will create an overlay for ***FAST***, called a wizard, which will guide the user through the steps necessary to create and analyze a work schedule. Using a dialog method, the user answers questions and completes forms or tables which the program then converts into a schedule file. The program then presents the user with a menu of output forms such as a graph of results and a tabular summary. In addition to the standard methods used to create an irregular schedule, the wizard will have specialized features for creating regular rotating shifts that follow a predictable pattern for those operations that have a set schedule.

The final initiative underway is to provide a standard human factors fatigue questionnaire to aid accident investigators in gathering the multiple threads of information necessary to evaluate fatigue as a contributing factor. The system will permit the investigator to create a data base of information for each accident. As the investigator gathers data and interviews workers and witnesses, the program prompts the investigator with questions and permits electronic recording of answers. The program guides the investigator to ask about the person's typical sleep and rest patterns, about medical conditions and medications being taken, and about the particular events leading up to the accident under investigation. The focus is on garnering data necessary to do a fatigue analysis and should be administered to subjects close to the time of the accident when memory for events prior to the accident is fresh. The program organizes all the responses into a searchable data base and ports the schedule information into ***FAST*** for fatigue analysis.

CONCLUSIONS

Fatigue management in transportation should be an iterative process involving all the stakeholders in the problem: management, labor, and government regulators. At each stage in the process – analysis, understanding, commitment, change, and evaluation – tools are needed to objectively assess potential fatigue and design alternatives that work to reduce that fatigue. A major new initiative involves using mathematical models of fatigue to serve as that objective metric. The models take information about work schedules and sleep schedules, if available, and project the impact of sleep duration and timing on cognitive capacity at different times of the day. When only work schedule data are available, another algorithm is used to estimate likely sleep patterns under the work schedule. The US Department of Defense has sponsored the development of such a model – the **SAFTE** model – and a software tool based on the model – the Fatigue Avoidance Scheduling Tool, or ***FAST*** – that has been validated against laboratory measures of cognitive performance. The Federal Railroad Administration has sponsored work to enhance the ***FAST*** software with several features to adapt it to the transportation environment and to collect data to test the ability of a fatigue model such as **SAFTE/*FAST*** to predict fatigue related accidents. Studies are underway to test the predictive validity of the tool and to calibrate it for fatigue related railway accidents and incidents. Other projects will develop associated tools to improve usability and interoperability with other scheduling software.

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