# SAND REPORT

SAND2005-6569
Unlimited Release
Printed October 2005

# Human Performance Modeling for System of Systems Analytics: Soldier Fatigue

Craig R. Lawton, Dwight P. Miller, James E. Campbell

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
A Lockheed Martin Company, for the United States Department of
Energy under Contract DE-AC04-94AL85000.

Sandia National Laboratories

*Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.*

SAND2005-6569
Unlimited Release
Printed October 2005

# Human Performance Modeling for System of Systems Analytics: Soldier Fatigue

**Craig R. Lawton**
**Dwight P. Miller**
**James E. Campbell**

**Sandia National Laboratories**

**Abstract**: The military has identified Human Performance Modeling (HPM) as a significant requirement and challenge of future systems modeling and analysis initiatives as can be seen in the Department of Defense's (DoD) Defense Modeling and Simulation Office's (DMSO) Master Plan (DoD 5000.59-P 1995). To this goal, the military is currently spending millions of dollars on programs devoted to HPM in various military contexts. Examples include the Human Performance Modeling Integration (HPMI) program within the Air Force Research Laboratory, which focuses on integrating HPMs with constructive models of systems (e.g. cockpit simulations) and the Navy's Human Performance Center (HPC) established in September 2003. Nearly all of these initiatives focus on the interface between humans and a single system. This is insufficient in the era of highly complex network centric SoS. This report presents research and development in the area of HPM in a system-of-systems (SoS). Specifically, this report addresses modeling soldier fatigue and the potential impacts soldier fatigue can have on SoS performance.

# TABLE OF CONTENTS

## LIST OF FIGURES



## LIST OF TABLES

# 1. Introduction

Current System of Systems (SoS) analysis efforts at Sandia National Laboratories (SNL) capture multiple performance attributes of military hardware systems, such as mobility and lethality in the context of user-defined scenarios. This capability is state-of-the-art and unique to SNL. However, the analysis capability is focused on technological and sustainment systems; the contributions and performance capabilities of human operators are not included. The problem with this approach is that humans are the driving force behind most military operations. Not including them in any analysis may miss the largest performance factor of the SoS simulation. When we considered the largest determinants of human performance in military scenarios, cognitive fatigue was noted as the leading contributor. In this report, we will present the results of a late-start LDRD effort to develop a methodology for integrating soldier fatigue with the current SoS modeling and simulation toolset.

Significant research has been devoted to human fatigue in a military context. This research has led to the development of biomathematical models intended to capture the effects of work-rest schedules, sleep deprivation, circadian rhythms, and sleep-replenishment cycles on perceived sleepiness and performance. The goal of this project is to use this research as the basis for estimating fatigue in humans and quantifying the potential impact of fatigue on SoS performance (e.g. the performance of a company within the Unit of Action force structure). The fundamental approach to achieve this goal is to assess the current state of human fatigue modeling in the open literature and select the most promising models that will support representing soldiers as elements within the simulation linked to combat and support platforms. This will allow the modeling of task failure rate in soldiers based on biomathematical models. A task failure is assumed to be a failure that leads to a system abort. Each soldier has a baseline task failure rate at maximum alertness. As a mission scenario unfolds and soldiers are deprived of sleep, their task failure rates increase. The increase in failure rate is estimated by a biomathematical model of the effects of sleep deprivation on task performance. This approach allows for the assessment of the impact of human fatigue on platform and SoS performance (e.g. operational availability).

A survey of the research and development devoted to human fatigue modeling will be presented in Section 2. This will be followed by a brief review of the current SoS simulation and analysis methodology in section 3. Section 4 will present a preliminary set of experiments and results demonstrating the utility of the inclusion of human fatigue modeling in the SoS methodology. In the final section, Section 5, future considerations will be addressed.

# 2. Fatigue Models Found in the Open Literature

This section summarizes current fatigue models that may be suitable for inclusion in the SoS modeling structure. Please note that the models described herein address cognitive fatigue, not fatigue resulting from physical labor.

## 2.1 The Two-Process Model

Developed initially for the sleep-research field, Achermann's two-process model resides at the basis of many models that address the regulation of fatigue and performance. Based on electroencephalographic slow-wave data collected during non-REM sleep, the model includes a linear interaction of homeostatic and circadian processes and an exponential sleep-inertia component. In 2003, the software associated with this model did not have a standard interface and could not be updated in real-time [1].

## 2.2 Sleep/Wake Predictor Model

Akerstedt developed this model using empirical subjective alertness data from altered sleep/wake patterns. It assumes an eight-hour sleep period to begin, an exponential fall in alertness during wakefulness, followed by an exponential rise in alertness during sleep. It uses a circadian rhythm peak alertness at 4:48 PM, and an exponential sleep-inertia factor. The model was developed for sleep researchers, companies demanding irregular work schedules, and organizations governing safe work-hour regulations. The software allows real-time updates and has screen outputs that include sleep latency, duration and bedtime, as well as alertness and performance curves [1].

## 2.3 System for Aircrew Fatigue Evaluation (SAFE)

Developed primarily for aviation operation applications, the SAFE model grew out of laboratory experiments and was fine tuned using long-haul flight operational data. The model is a "combination of sinusoidal component in time of day and a cubic trend in time since sleep." Currently being used by the UK Civil Aviation Authority, the interface displays results graphically in two-week time frames, alertness levels are color-coded, and the existing version of the model (in 2003) did not accept real-time updates [1].

## 2.4 Interactive Neurobehavioral Model

This model uses a combination of circadian, homeostatic, and sleep-inertia components to estimate neurobehavioral performance. It assumes initial conditions of eight hours of sleep in darkness and 16 hours of wakefulness in 150 lux illumination. Validation studies with human subjects include varying light patterns, jet lag, sleep deprivation, and non-24 hour schedules. The PC-compatible software allows inputs of light levels and sleep/wake times, while the output graphs performance, alertness, and minimum core body temperature. This model is used by NASA and DoD researchers [1].

## 2.5 SAIC Human Performance Cognitive Model (HPCM)

This holistic model considers fatigue as only one of several stressors that can have a limiting influence on human performance in information operations (e.g. decision-making, target selection, situation analysis, mission analysis, and communication). The HPCM can produce as outputs minute-to-minute estimates of human effectiveness (as a percentage of maximum), time delay, and decision-making styles (called types by the authors). The model has been implemented in Windows-compatible simulation software, which has a user interface consisting of input and parameter adjustment screens and a run-time output screen, whose minute-to-minute estimates are entered into an Excel spreadsheet [2].

The HPCM assumes an underlying naturalistic decision-making process, as stipulated by Klein and colleagues [3,4]. In addition to the influences of sleep-deprivation and fatigue on performance, the model accounts for the stressors of 1) time pressure (i.e. having less than optimal time to perform a task), 2) personality (aggressive/risk tolerant vs. non-aggressive/risk averse), and 3) threats of failure and confidence builders (e.g. hearing that your forces achieved a goal). The model also accounts for significant modulators of stress, including training, experience, and intelligence.

### 2.6 SAFTE

For the purposes of this summary, the sleep-deprivation and fatigue stressors are the most interesting part of the HPCM, described in section 2.5. These factors are handled by the SAFTE (Sleep, Activity, Fatigue, and Task Effectiveness) model, developed by Steven Hursh and colleagues at SAIC and Johns Hopkins University School of Medicine. It has been under development in various forms since 1989, and is probably the most complex and sophisticated fatigue model extant. It uses a circadian rhythm function, a circadian sleep propensity function, and a method to extend predictions to task effectiveness and cognitive capability. The SAFTE applies to information operations only and makes no claims for applying to physical-exertion activities or other kinds of work.

Under sustained combat conditions, sleep deprivation and fatigue are natural human hazards. Tasks most sensitive to sleep deprivation and fatigue are cognitive operations, such as decision-making, logical reasoning, memory, and mathematics. According to Hursh [2]:

> "...studies of sleep patterns in simulated combat at the National Training Center indicate that commanders (Lt. Colonels and Colonels) in force on force operations average just over four hours of sleep per day, about half of the normal requirement for fully effective performance."

The SAFTE model assumes a cognitive reservoir that maintains a balance of effective performance units. The reservoir is set at the beginning of the simulation, based on the sleep debt (if applicable) accumulated in the days prior to the simulation start time. During sleep, units accumulate at rates responsive to the existing sleep deficit (i.e. more quickly for the initial sleep than prolonged sleep). Units are subtracted during time awake in a linear manner until a steady state is achieved after three days of reduced sleep of 4 hours per night. Effectiveness is a minute-by-minute mathematical calculation based on the cognitive reservoir level, circadian rhythm, and motivation effects.

The Air Force Research Laboratory in conjunction with the Air Force Operational Test and Evaluation Center conducted a wartime aircrew fatigue assessment during C-17 missions to Afghanistan during Operation Enduring Freedom [6]. Data collection included psychomotor tests, activity monitors, logbooks, and subjective self-assessments.

## 2.7 CAS – Circadian Alertness Simulator

The CAS model allows for the assessment of fatigue risk (usually for the transportation industry) based on sleep-wake patterns. The model is based on the Two-Process Model. A homeostatic component is combined with a circadian-rhythm component to calculate an alertness curve. Sleep-wake data and the operator's individual chronotype characteristics (short vs. long sleeper, morning type vs. evening type, etc.) and napping capability are used as input to the model. Output includes graphical plots of predicted alertness as a function of time, the impact of naps at different times of day, frequency distributions of simulated alertness during work and commuting activities, and distributions of cumulative fatigue risk scores for large groups of workers.

The model does not account for different kinds of work or other stressors that may influence alertness or fatigue. This approach is best used for determining optimal work schedules for a known population of workers, who can supply individual data on their sleep/wake patterns. It is also used in accident analysis to inquire whether fatigue was in influencing factor.

The validation approach described in [5] seemed to be circular reasoning. This model performed least well in the independent model comparison of six fatigue models, conducted at a Fatigue and Performance Workshop, where the models were used to predict results from four standard scenarios [13].

## 2.8 Galaxy Aviation Maintenance Fatigue & Performance Study

In 2001, Galaxy Scientific Corp. published a report on the results of an FAA-sponsored study looking at predictors of human performance in commercial aviation maintenance workers [8]. Variables studied included average daily sleep, occupational extreme temperatures, lighting, noise, and alertness. Twenty-five commercial-airline, maintenance personnel wore activity-measuring devices for 14 days, which yielded an average sleep duration of 5 hours 7 minutes per day. This finding was consistent with previous studies. Twenty-three technicians wore measurement devices to monitor temperature, ambient lighting, and sound levels while working. All 48 filled out questionnaires about working conditions and personal habits. Roughly half of the participants worked swing/night shifts. Workers were unaware of the average actual sleep duration, and claimed an average 6.26 hours in the questionnaire. The authors point out that the actual measurements did not include initial "tossing and turning" as sleep, and that people typically estimate their sleep time by inclusive clock time. Regardless, the authors concluded that actual sleep duration was inadequate for the required work and recommended remedial actions that could be taken. The authors offered a simple mathematical model describing how temperature, sound, light and fatigue impact the probability of an error occurring. Fatigue had an impact an order of magnitude higher than any of the other factors.

## 2.9 Dynamic Bayesian Network Real-Time Fatigue Modeling and Monitoring

Lan, Qiang, and Looney developed a dynamic fatigue model based on hierarchical Bayesian Networks in 2003. In order to account for the changes in fatigue over time, the authors improved upon their previous static model [9], which utilized contextual nodes, such as temperature, light, anxiety, and workload; and observation nodes, such as gaze, head tilt, and yawn frequency.

Rather than step-function outputs, as found with the static model, the fatigue predictions of the dynamic model [10] show curvilinear and asymptotic profiles, which more realistically model the accumulation of fatigue over time. The authors are currently validating the model using human subjects.

**2.10 Dawson and Fletcher's FAID Model of Work-Related Fatigue**

Based on the work of Borbely and Daan, Dawson and Fletcher analyze fatigue based on the linear accumulation of hours of prior wakefulness and sinusoidal components from circadian rhythms [11,12]. The circadian component assumes a 24-hour periodicity with a maximum fatigue rate of 2.0 units per hour starting at 0500 hours and a minimum value of 1.0 unit per hours at 1700 hours. Therefore, the increase in fatigue across a work period is not linear, but dependent upon the time of day. Quality of sleep varies as a function of the time of sleep onset and the amount of sleep. Thus, the model calculates fatigue as an algebraic function of fatigue and recovery functions, given the initial conditions of prior work over the previous week. Saturation occurs when full recovery has occurred, regardless of additional sleep beyond 10-11 hours. The model has been used to evaluate alternative work schedules for standard and rotating work schedules and for commercial-aviation schedules. The model's output indicates that for identical work durations, time of work onset and shift rotation can increase work-related fatigue by up to 60 percent. The model is described in detail in [11], and empirical evaluations are reported in [ 12].

The second article in the series [12] addresses model evaluations using sleep-deprivation experiments and comparisons to current scheduling recommendations found in the literature. Fairly high concurrence was attained between model predictions and performance after cumulative sleep deprivation of 4-5 hours per night for 7 nights. Model predictions were found to correlate highly with psychomotor vigilance task (PVT) lapses ($r = 0.92$) and slowest 10% of reaction time responses ($r = 0.91$), as well as sleep latency ($r = -0.97$). When model predictions were compared to published data from continuous sleep deprivation over a 64-hour period, correlations were obtained with vigilance ($r = -0.75$), performance ($r = -0.75$), sleepiness ($r = 0.82$), and tiredness ($r = -0.79$). The model also predicts fatigue levels for workers on a rotating shift schedule. Using the results of model outputs the authors make several recommendations about shiftwork. For example, they state that as few night shifts as possible be worked in succession, with the maximum of three. They also suggest that permanent night shift work should be avioided, as should single days off between night shifts, and that forward rotation of shifts (morning, day, night) are preferable to backward rotation (morning, night, day). The authors suggest that further improvements in accuracy could be attained if day-to-day changes in circadian rhythms can be accounted for (e.g. crossing time zones).

**2.11 Comparison of Six Models of Fatigue at 2002 Workshop**

A Fatigue and Performance Modeling Workshop was held in Seattle, WA on June 13 and 14, 2002. Predictions of human fatigue and performance were solicited for four different sleep/wake/work scenarios from the mathematical modeling community. Six modeling teams responded and their predictions were compared to empirical data collected from experiments for the four scenarios. A fifth scenario was given to the modeling teams at the Workshop. The teams that competed were:

| | |
|---|---|
| A. CHS Chronic Fatigue Model | Spencer & Belyavin |
| B. CAS | Moore-Ede |
| C. FAID | Dawson & Fletcher |
| D. Interactive Neurobehavioral Model | Jewett & Kronauer |
| E. SAFTE | Hursh |
| F. Sleep/Wake Predictor | Folkhard & Akerstedt |

The five scenarios used for prediction comparisons used healthy male and female non-drug users as subjects in the following wake/sleep/work profiles:

Scenario 1: 88 hours of extended wafefulness
n=13 without naps, n=12 with 2-hour naps every 12 hours

Scenario 2: 14 days of partial sleep deprivation
n=13 sleep resticted to 4 hours/day, n=11 sleep restricted to 6 hours/day

Scenario 3: Freight locomotive engineers on the Extra Board (on-call substitutes)
n=10 male engineers over 14 days kept daily logs, no napping was allowed during work periods, caffeine was consumed ad libitum

Scenario 4: Long-range flight operations
Theoretical 20-hour flights, followed by 50-hour layover, followed by 18-hour return flight, no drugs used except caffeine

Scenario 5: 7 days of sleep restriction followed by 3 days recovery
n=16 slept 7 hours/day, n=18 slept 3 hours/day, followed by sleep from 23:00 to 07:00. This scenario was presented at the Workshop

Dependent measures included subjective sleepiness (Karolinska Sleepiness Scale, or KSS) and a psychomotor vigilance task (PVT), which measures time lapses in responses to stimuli. In both metrics, larger scores indicate increased fatigue. Ref. 12 publishes all of the graphical comparisons between empirical data and model predictions, and summarizes the mean square error (MSE) and relative root-mean-squared error (RRMSE) between actual and predicted sleepiness and performance for the six models. Differences between models were not statistically compared, however numerical differences were generally small compared to the differences between model predictions and empirical data.

Results In scenario 1, model B had the lowest MSE and RRMSE for sleepiness, while model D edged out the others for lowest error in performance. In scenario 2, model E predicted sleepiness best, while model C was had the lowest error for performance. However, when sleep inertia was removed (all the data points immediately following awakening were removed from the analysis) in scenario 2, [revised] model E was the winner. Scenario 3 yielded a virtual dead heat for models F, B, and E for predicting alertness (model A was not used in this scenario). No experimental data were available for comparisons in scenario 4, and modeling teams C and D did not provide predictions. The remaining four models are graphically compared in [13], Fig. 15, pg. A30. For scenario 5, teams had to prepare their predictions by the end of the first day of the workshop (model E was excluded because prior to the workshop, it was revised and optimized using experimental data for the scenario). Model D provided the least MSE and RRMSE for comparisons with the experimental data in scenario 5.

In summary, the authors concluded that the models were capable of predicting the data of scenarios 1 and 3 fairly well, and much better than expected, given the complexities of the neurobiology of fatigue and performance. Chronic sleep-restriction scenarios caused problems for all of the models. The authors suggest that "given the relevance of chronic sleep loss in many operational settings, this may be an area deserving priority for further model development.

### 2.12 Selecting a Fatigue Model for Experimentation

There are two justifiable methods for selecting the most appropriate model for demonstration purposes in the latter sections of this report. First, select the model that achieves the best fit to human data for the scenario that best approximates the scenario of application. The standard Future Combat System Unit of Action scenario consists of a 72-hour period of high-operational-tempo activity. This application is most similar to scenario 1 in the 2002 workshop, which has sustained activities without sleep for 88 hours. The best performer in this test was the model D, the interactive neurobehavioral model. The second method of selection is to choose the model that was best overall in predicting sleepiness and performance across the scenarios. This was model E, the SAFTE model. For this reason, and considering the fact that the SAFTE model has been used frequently in military applications, it was chosen for the experimentation summarized in this report.

## 3. Review of SoS Simulation Methodology

A major step toward performing complex SoS analysis has been the development of a multi-system time-simulation capability. Key to the multi-system simulation capability has been the development of a State Model Object (SMO) that enables a system, its elements, and its functionality to be encapsulated for use in the simulation. State Model Objects can be the same objects that have been created in the static State Modeling System (SMS) or they can be created directly in the simulation application. The concept behind the multi-system simulation is illustrated in Figure 1.

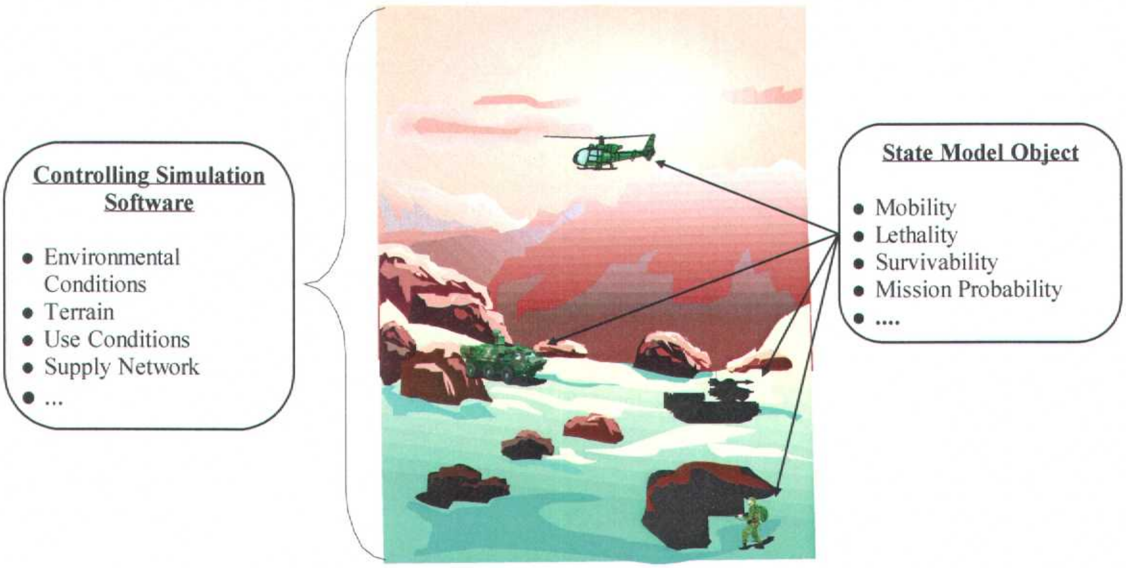


**Figure 1 Multi-System Simulation Concept**

Every system in the simulation is represented by an SMO which represents the system's functionality while the controlling simulation software provides needed information on environmental conditions, terrain, use conditions, supply network information, etc. A simplified view of the SMO simulation architecture is shown in Figure 2. The SMO is the central feature of the simulation with an SMO used to represent each system in the SoS being simulated. There is also a scenario model that describes the detailed scenarios that the systems will follow during the simulation. A combat-damage model provides a mechanism to simulate the effects of combat damage, ranging from damage to individual system primary elements to completely disabling the system. Finally, a supplies-and-services model provides a means for spare parts and consumables to move from system to system in the simulation and makes maintenance services available to systems requiring repairs. The following section discusses the components of the SMO Simulation.

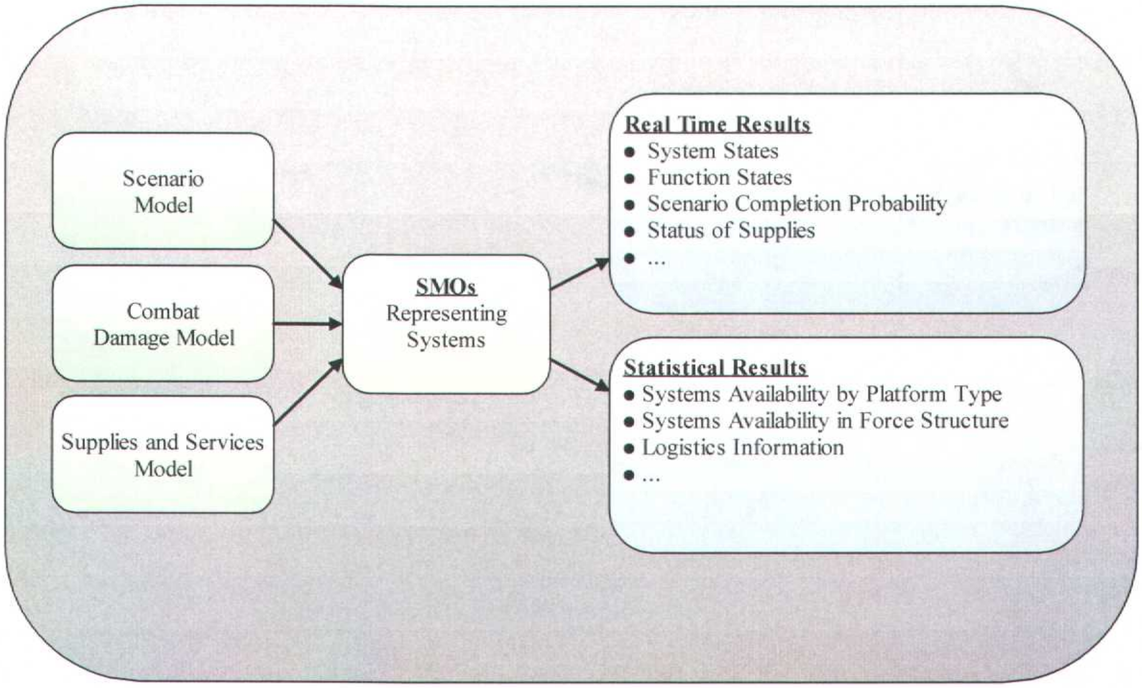


**Figure 2 SMO Simulation Architecture**

The SMO can be configured to represent a wide variety of systems. The types of systems that might be represented by the SMO include air vehicles, ground vehicles, manufacturing equipment, a soldier and the equipment he carries, etc. For modeling and simulation purposes, the SMO can be used to represent almost any system whose functionality can be described by the states of the system's elements.

The SMO is made up of a collection of elements that may be subsystems, components, failure modes, external conditions, or functional elements of other systems. The SMO can have multiple functions or measures of effectiveness (MOEs), such as mobility, communications, sensing, lethality, etc. This attribute makes this modeling system unique in the field. Furthermore, any function can itself have multiple states and is not restricted to success or failure. The state of any function is determined by the states of the elements that contribute to that function. The SMO simulation also provides an interface for managing dependencies between the SMOs. The SMO simulation is a time-step simulation where system states are evaluated and determined at each time step.

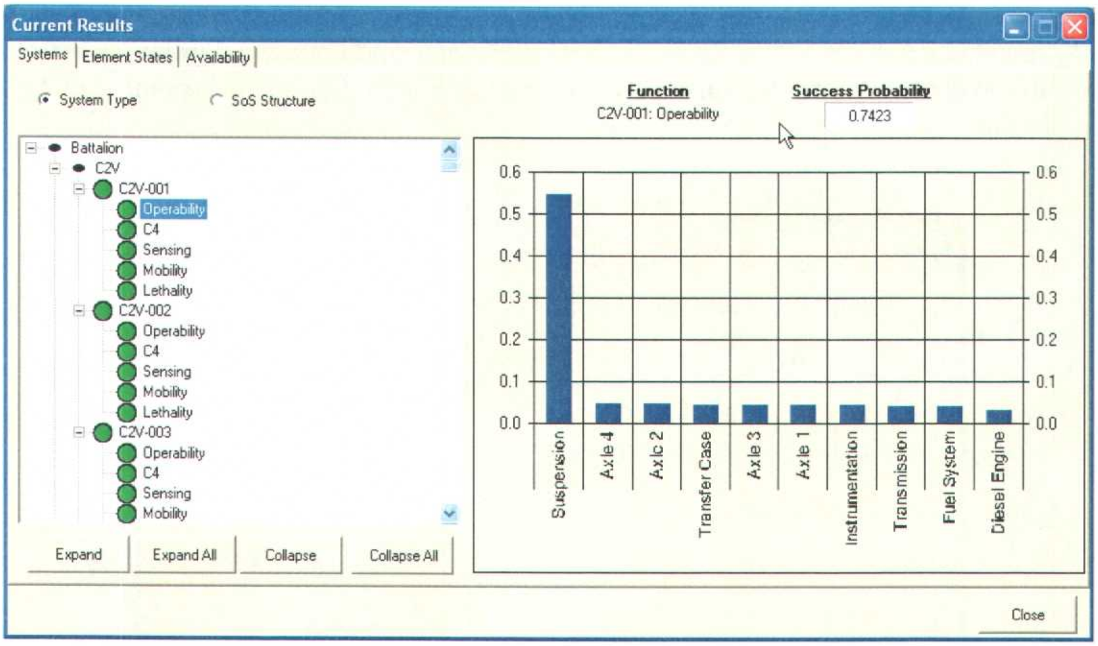


**Figure 3 Display of Functions by System**

Figure 3 shows systems and their functions in real time as the simulation proceeds. The tree structure on the left side can be shown with the systems organized by system type as is the case in Figure 3, or the systems can be organized within the system-of-systems structure. All functions are shown for each system. When a system function fails, the green circle beside that function turns red. If the function is reduced to an intermediate state (partially operable), the circle turns yellow. The right side of the window shows the probability of successful operation of the selected function for the remainder of the mission. Note that functions can be dependent on elements and functions of other systems. In Figure 3, in the upper right-hand portion, we can see that the probability that C2V-001 will remain operable for the remainder of the mission is 0.7423. Should C2V-001 lose operability, the most likely element failures are shown in the Pareto chart. Based on the results in Figure 3 and other summary results such as operational availability (both average and instantaneous), various performance measures of the SoS can be assessed over the duration of the scenario.

## 4. Experimentation and Results for Scenarios Including Soldier Fatigue

This section describes a simulation example that will form the basis representing soldiers and the impacts of fatigue. After the baseline example is described, the methodology for incorporating soldiers and soldier fatigue will be presented. This is followed by simulation and analysis of a set of scenarios quantifying the impacts of different levels of fatigue on SoS performance.

### 4.1 Simulation Example Problem Definition

For the purposes of demonstrating the impacts of soldier fatigue on SoS performance, a baseline SoS simulation the following example problem formed the basis for analysis. The example consists of a total of 40 systems with the types and numbers shown in Table 1. The example depicts a typical Headquarters Company (HHC) of the Future Combat Systems Unit of Action

(FCSUA) force structure. Note that there is a mixture of manned ground combat platforms, manned ground support platforms, unmanned air platforms, and unmanned ground platforms. This example will allow us to demonstrate the impact of human fatigue on a number of MOEs of varying platform types.

**Table 1 Systems in the Example Problem**

| System Type | Number |
|---|---|
| Command and Control Vehicle (C2V) | 5 |
| High Mobility Multipurpose Wheeled Vehicle for Command and Control (HMMWV-C2) | 4 |
| Unit Water Pod System (CAMEL) | 2 |
| Tank Rack (Fuel) | 2 |
| Infantry Carrier Vehicle (ICV) | 5 |
| Forward Repair and Maintenance Vehicle (FRMV) | 1 |
| Heavy Expanded Mobility Tactical Truck with Load Handling System (HEMTT-LHS) | 6 |
| Unmanned Air Vehicle Class 1 (UAV CL1) | 4 |
| Unmanned Air Vehicle Class 2 (UAV CL2) | 2 |
| Palletized Loading System with Trailer (PLS) | 4 |
| Medical Vehicle for Evacuation (MV-E) | 2 |
| Medical Vehicle for Treatment (MV-T) | 2 |
| MULE-Countermine (MULE-CM) | 1 |

Each system in the FCSUA is represented as a state model object in the SMO simulation. The ground vehicles all follow a scenario that consists of a 72-hour period of high-operational-tempo activity. The UAVs have 2-hour flights every eight hours for the 72-hour interval. The next step in developing this model is representing soldiers in a way that can relate their task effectiveness to the functionality of the systems.

### 4.2 Representing Soldier Fatigue in the SoS Simulation

The SMO and its functions are dependent on the elements that comprise the SMO. By representing the soldier as an *element* of the platform SMO, the availability of the SMO or one of its functions can be dependent on the soldier. In reality, crews of soldiers are allocated to platforms, each performing critical tasks. Table 2 includes the allocation of soldiers to platform types (note: the abbreviated functional title of the soldier is listed in the table).

**Table 2 Allocation of Soldiers to Platform Types**

| Platform | Personnel |
|---|---|
| C2V | VEH-CMDR<br>OPS-NCO<br>OPS-OFF<br>ISR-OFF<br>C4/SIG/DRIVER |
| CAMEL | MAINT-TECH |
| FRMV | MAINT-TECH-1<br>MAINT-TECH 2 |
| HEMTT_LHS | OPERATOR<br>DRIVER |
| HMMWV-C2 | OPERATIONS-TECH<br>DRIVER |
| ICV | VEH-CMDR<br>OPS-NCO<br>FIRES-NCO<br>ISR-NCO<br>C4-SIG-DRIVER<br>CDR<br>XO<br>ISR-SPC<br>ROBOTICS-TECH |
| MV-E | PA-OFF<br>HEALTH-CARE-TECH-1<br>HEALTH-CARE-TECH-2 |
| MV-E | PA-OFF<br>HEALTH-CARE-TECH-1<br>HEALTH-CARE-TECH-2 |
| Tank_Rack | SUSTAINMENT-TECH |
| UAV1 | UAV-OPERATOR |
| UAV2 | UAV-OPERATOR |
| HMMWV_SPT | OPERATIONS-TECH<br>DRIVER |

As the soldier fails to perform critical tasks, they impact the availability of the platform. For the purposes of demonstration, a nominal rate of one failure impacting platform availability per 100 hours was assumed for all soldiers (note: although we have no experimental data to support this value it is a reasonable value to demonstrate impact). The real question is, what is the functional relationship between fatigue and soldier performance? To answer this question we have chosen to utilize, for the purposes of this example problem, the approach taken by the developers of the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) model, developed by Hursch and associates. The SAFTE model uses a linear model to represent performance degradation as a function of hours on task. That is, as soldiers are deprived of sleep, after an eight-hour sleep period, their cognitive performance decreases linearly over time and their critical task failure rate (impacting platform availability increases). The slope of the line is based on actual experimentation involving human cognitive performance on arithmetic tasks during periods of sleep deprivation. Figure 4 depicts such a regression line fitted to actual data (dots) for a period of 72 hours.

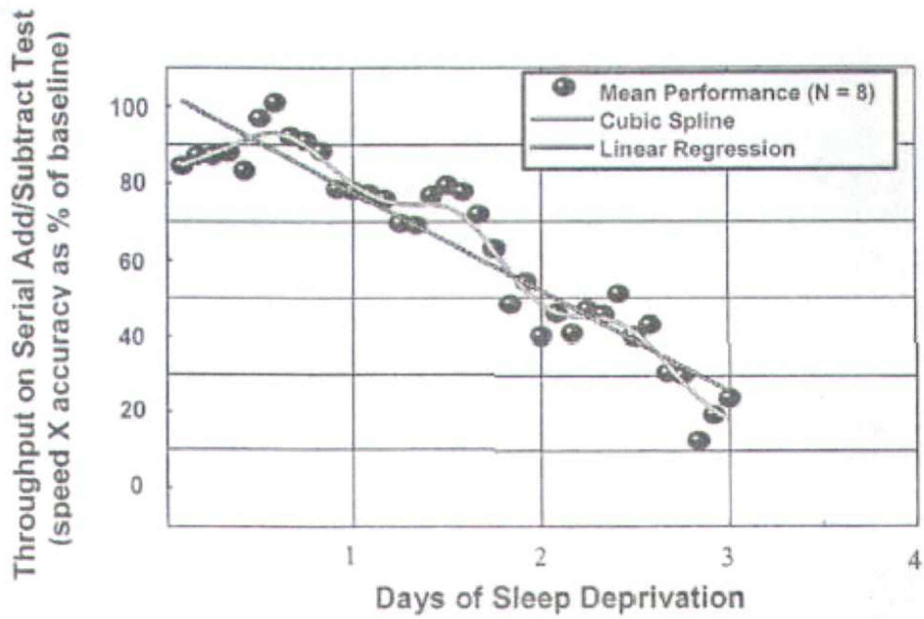


Fig. 2. Performance decrement on the Serial Addition/Subtraction Task across 72 h of sleep deprivation.

**Figure 4 SAFTE Sleep Deprivation Performance Decrement Model**

The actual data appear to be more cubic than linear; however, the developers of SAFTE felt a linear representation was sufficient (see [1] for a full discussion of the SAFTE and the underlying assumptions). For purposes of demonstration we chose to utilize the same linear performance-decrement model as was the basis for SAFTE. It should be noted that different decrement models can easily be accommodated in the SoS simulation. For the SoS simulation, the performance decrement model provides the same rate of increase in task failure of the soldier element, as was modeled by SAFTE.

The increase in task-failure rate is modeled by creating fatigue-inducing conditions in the simulation scenario. In this example, three fatigue conditions were created representing multiplicative increases in task-failure rate commensurate with the performance-decrement model. Each fatigue condition is intended to correspond with a period of time during the 72 hour mission. This allows for a scenario to be created that would correspond with different levels of fatigue due to varying periods of sleep deprivation. For example, for the first 18 hours, performance is not decremented at all. During the next 18 hours, performance is decremented by 20%, as indicated by the performance decrement model. Each of the following two 18-hour period is affected by an additional 20% decrement until the soldiers are performing at 40% effectiveness at the end of the scenario. The sleep-deprivation scenario is applied to all the platforms with soldier elements. It should be noted that in this demonstration the mission scenario is broken up into three phases of sleep deprivation, the number of phases could be as many as the user desires (incidentally, the cubic data in Figure 4 suggests three performance peaks followed by rapid decline).

### 4.3 Experiments and Results

For this demonstration, three experiments were constructed:

1. A Baseline model, where soldiers do not experience sleep deprivation and soldiers fail at a constant rate.
2. Experiment 1, where soldiers are not allowed to sleep until the 54$^{th}$ hour of the mission
3. Experiment 2, where soldiers are deprived of sleep for the entire mission (72 hours).

Each experiment consisted of a 72-hour mission and was run for 500 replications. As elements (soldiers as well as hardware components) fail, systems are not available, and a measurement of the systems operational availability (Ao) can be computed.

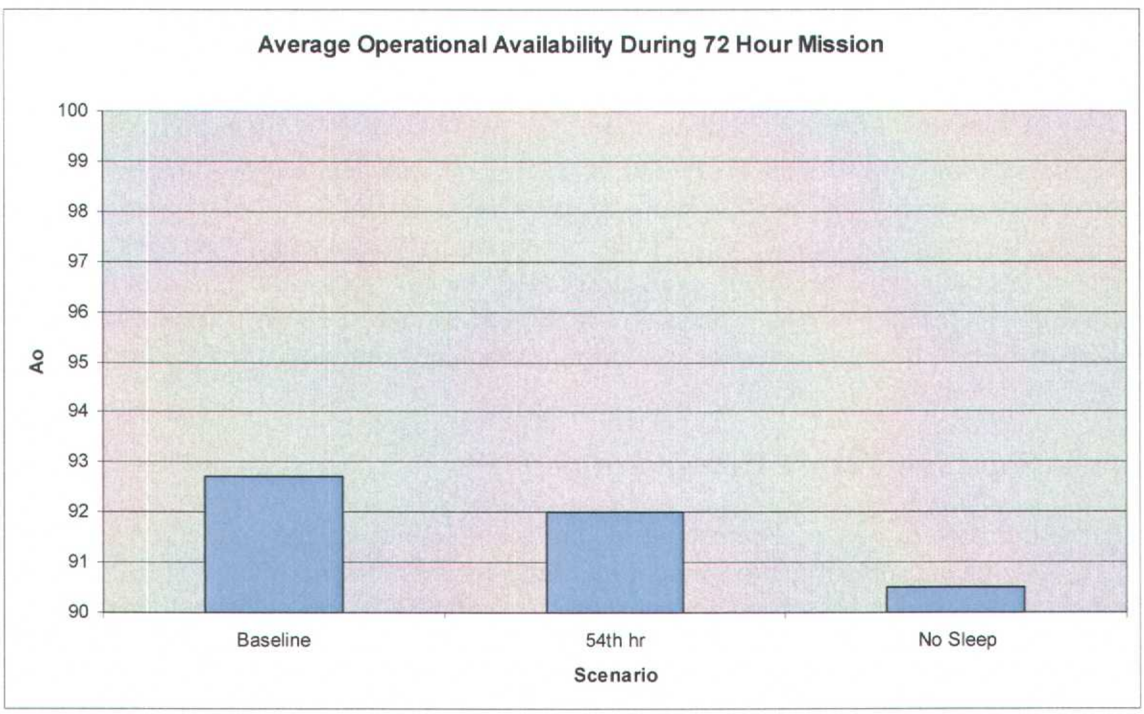


**Figure 5 Average Operational Availability**

Figure 5 plots the average Ao across all platforms in the company over the 500 replications. There is a difference of approximately 2.2% between the Baseline experiment and the experiment without sleep. While this may not seem like a huge difference, it represents a 30% increase in unavailability. The United States Army invests significant budgetary funds to accomplish a similar decrease in unavailability.

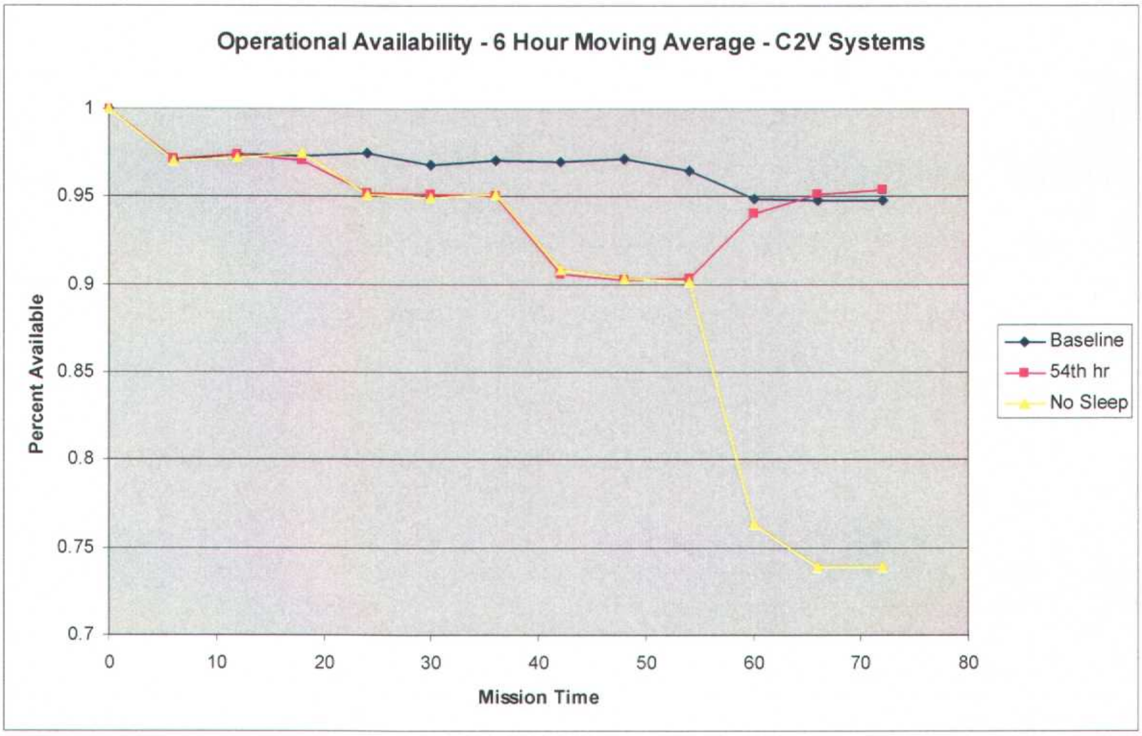


**Figure 6 Instantaneous Operational Availability**

Figure 6 plots the moving average every 6 hours for operational availability (an approximation of instantaneous availability) of the C2V platforms over the course of the 72-hour mission for each of the three experiments, after 500 replications. The most striking aspect when looking at the chart is the extremely rapid decline in availability after the $54^{th}$ hour. This is due to the compounding effect that lack of sleep has on soldier performance. The experiment where sleep occurs are at the $54^{th}$ hour indicates that performance would significantly benefit from moderate sleep at that point in the mission.

## 5. Conclusions and Future Considerations

The goal of this project was to demonstrate the impact of soldier fatigue on the performance of an FCS UA, using an SoS simulation-modeling framework that incorporates elements of the mathematical models that have been developed to simulate the effects of sleep deprivation on humans. Using an approximation of the performance-decrement function characterized by the SAFTE fatigue model, the temporal multiplicative impacts of sleep deficit on soldier task performance were included in a small example simulation consisting of 40 systems and 116 soldiers. Accommodating sufficient run-time, this analysis could easily be scaled up to an entire unit of action consisting of approximately 1500 systems and 3500 soldiers.

The example analysis demonstrates very clearly that the SMO simulation framework that has been developed at SNL can be augmented with mathematical models drawn from the soldier fatigue research base and that this augmented methodology can clearly quantify the impact of fatigue on the performance of a SoS.

One alternative to representing the soldier as an element of a system is to represent the soldier as a subsystem or system in and of itself. That is, the soldier would be modeled autonomously allowing the soldier to have independent elements and functions. When simulating failure due to only fatigue, this level of flexibility is not necessary. But if more sophisticated cognitive modeling of soldier is necessary in order to model numerous human failure modes (e.g. lack of training, stress, injury) or represent more complex interdependencies between and among other systems, then modeling the soldier as a system or subsystem will be required. Modeling the soldier as an independent system or subsystem would also allow for more detailed treatment of sleep, activity, and sleep-replenishment functions in the human system (e.g. individualized sleep schedules could be analyzed). As we begin to model the cognitive system in an SoS simulation framework this will likely be the direction.

## 6.0 References


1. Mallis, M.M, Medjal, S., Nguyen, T.T., & Dinges, D.F. (2003) Summary of the key features of seven biomathematical models of human fatigue and performance. *Aviation Space and Environmental Medicine, 75*:3 Supplement, A4-A14.

2. Hursh, S.R.& Bell, G.B. (2001) *Human Performance Cognitive Model for Air Force Information Operations*, SAIC, December 2001.

3. Klein, G. (1997). The current statusof the naturalistic decision-making framework. In Flin, et al. (eds.) *Decision-making under stress.* Brookfield: Ashgate.

4. Klein, G. (1996) The effect of acute stressors on decision-making. In Driskell & Salas (eds.) *Stress and human performance*. Mahwah: Earlbaum.

5. Hursh, S.R. (2004) Non-Prescriptive Tools for Effective Fatigue Management. Slide presentation at the DOT Human Factors Coordinating Committee, June 23, 2004.

6. Guttkuhn, R, et al. (2003) Human fatigue risk simulations in 24/7 operations. In Chick, et al. (eds.), Proceedings of the 2003 Winter Simulation Conference, pp. 1838-1842.

7. Moore-Ede, M. et al. (2004) Circadian Alertness Simulator for fatigue risk assessment in transportation: Application to reduce frequency and severity of truck accidents, Aviation, Space, and Environmental Medicine (in press).

8. Hall, S., Johnson, W. B., & Watson, J. (2001) Evaluation of aviation maintenance working environments, fatigue, and human performance, R04-00641-A, Galaxy Scientific Corp.

9. Lan, P., Ji, Q., and Looney, C. (2002) Information fusion with Bayesian belief networks for monitoring human fatigue. In *Proceedings of the 5th International Conference on Information Fusion (FUSION 2002)*, International Society of Infromation Fusin, Annapolis MD.

10. Lan, P., Ji, Q., and Looney, C. (2003). Non-intrusive real time human fatigue modeling and monitoring, *Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society*, Santa Monica CA.

11. Dawson, D. & Fletcher, A. (2001) A quantitative model of work-related fatigue: Background and definition, *Ergonomics*, *44*:2.

12. Fletcher, A. & Dawson, D. (2001) A quantitative model of work-related fatigue: Empirical evaluation, *Ergonomics*, *44*:5, 475-488.

13. Van Dongen, H.P.A. (2004) Comparison of mathematical model predictions to experimental data of fatigue and performance. *Aviation Space and Environmental Medicine, 75*:3 Supplement, A15-A36.

Distribution:

(1) MS 0188 D. Chavez, LDRD Office, 1030
(1) MS 0748 Chris Atcitty, 06861
(1) MS 1011 Robert Cranwell, 06642
(1) MS 1011 Dennis Anderson, 06642
(1) MS 1011 James Campbell, 06642
(1) MS 1011 Leon Chapman, 06642
(1) MS 1011 Craig Lawton, 06642
(1) MS 1011 Dwight Miller, 06642
(1) MS 9018 Central Technical Files, 8945-1
(2) MS 0899 Technical Library, 9616