Integrated Model of Fatigue and C-17 Approach and Landing Operations

Bella Z. Veksler
(b.veksler@tier1performance.com)
Tier1 Performance Solutions
Covington, KY 41011 USA

Megan B. Morris
(megan.morris.3@us.af.mil)
Air Force Research Laboratory
WPAFB, OH 45433 USA

Michael A. Krusmark
(michael.krusmark.ctr@us.af.mil)
L3Harris Technologies
Melbourne, FL 32919 USA

Glenn Gunzelmann
(glenn.gunzelmann@us.af.mil)
Air Force Research Laboratory
WPAFB, OH 45433 USA

Abstract

Fatigue is a common occurrence in several occupational fields, often resulting in operator performance and health issues. Biomathematical models of fatigue have become useful tools in several fatigue risk management programs. However, these tools still have limitations in terms of identifying specific performance outcomes affected by fatigue, as well as individualizing fatigue estimates to individual operators. The integration of computational cognitive models and biomathematical models can help solve these issues in a complex operational context. The current effort aims to develop an integrated model of fatigue in the context of C-17 approach and landing operations. Specifically, we integrate a biomathematical fatigue model with a task network model to estimate performance degradation due to fatigue. The following paper outlines the development of the task network model and integration with the biomathematical fatigue model.

Keywords: task network model; biomathematical fatigue model; fatigue; aviation

Fatigue is a pervasive issue in work environments involving factors such as long work hours, shift schedules, circadian desynchrony, and high workload tempo, factors common in transportation, healthcare, and law enforcement, among other fields. Fatigue often results in performance degradations and can have significant negative effects on operator health, especially if fatigue is chronic in nature (Belenky, Lamp, Hemp, & Zaslona, 2014; Craig & Cooper, 1992). Biomathematical fatigue models are promising predictive tools in fatigue risk management (FRM) programs in high-risk operational settings. These models commonly use factors such as homeostatic regulation, sleep/wake schedules, and circadian rhythm to create general predictions of fatigue for operators (Mallis, Mejdal, Nguyen, & Dinges, 2004). However, these models have limitations that affect the accuracy of fatigue predictions. They tend to predict general performance outcomes (e.g., cognitive effectiveness) that might not relate directly to risk in an operational setting. Additionally, these models commonly lack individualization; rather, they give fatigue predictions for an "average" operator (Civil Aviation Safety Authority, 2014; Dawson, Darwent, & Roach, 2016; Mallis et al., 2004). Computational cognitive models can provide a cost-effective and flexible means to explore the usability of systems through simulation (Pew, 2007). Recently, research has successfully integrated biomathematical models of fatigue with cognitive architectures (e.g., Gunzelmann, Veksler, Walsh, & Gluck, 2015). In the current effort, we work toward developing an integrated model that can pinpoint specific performance degradations due to fatigue in a complex real-world environment, and allows the inclusion of individual difference modulations. Specifically, we integrate a biomathematical fatigue model with a task network model (Laughery, Archer, Plott, & Dahn, 2000) to predict C-17 aircraft approach and landing performance degradations.

Background

C-17 mobility pilots and aircrew are especially susceptible to fatigue given unique characteristics of the operational environment. Basic crews and augmented crews have flight duty periods of up to 16 and 24 hours, respectively. Flight legs commonly cross multiple time zones during missions and missions comprising multiple legs often last several days. Research suggests mobility aircrew are commonly fatigued during missions and believe that changes need to be made in the mobility community to address fatigue (Morris, Howland, Amaddio, & Gunzelmann, 2020; Morris, Veksler et al., 2020). Currently, the United States Air Force Air Mobility Command (AMC) uses the Fatigue Avoidance Scheduling Tool (FAST®; Hursh, Balkin, Miller, & Eddy, 2004) and underpinning biomathematical fatigue model, Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE™; Hursh, Redmond, et al., 2004) to develop mission effectiveness graphs that balance fatigue with operational needs and recommend sleep schedules for aircrew based on mission information (e.g., flight leg start and end times, time zones, light). The SAFTE model includes a circadian process affecting sleep regulation and performance. Within the model there is a reservoir capacity which refers to an individual's maximal capacity to perform tasks. This capacity is affected by sleep and wakefulness. When an individual is awake, the reservoir level decreases, and when an individual is asleep the reservoir is replenished. Accumulation in the reservoir is affected by sleep intensity and sleep quality. Sleep intensity is a function of time-of-day (circadian phase) and the current reservoir level (sleep debt). Performance is affected by the sleep reservoir, circadian phase, and sleep inertia. Performance output from the model is a general cognitive effectiveness in the form of a percentage from 0 to 100% (Hursh, Redmond, et al., 2004). Aircrew can use the resulting mission effectiveness graph from FAST and SAFTE to plan fatigue mitigation strategies. It is not known which performance metrics are affected in C-17 pilot operation, nor is there currently a mechanism to individualize these predictions within AMC's general risk management program. As a result, additional tools are needed to provide insights into specific performance metrics that are likely to be affected by fatigue and have the ability to incorporate individual difference factors that affect fatigue.

The current C-17 approach and landing model was developed using a task network model. These models are comprised of nodes and connections that let activity flow through the network and provide an efficient way of simulating the complexities of operator/system designs (Hansberger & Barnette, 2005; Schunk, 2000; Swoboda, Katz, & Kilduff, 2005). The sequencing of various tasks and subtasks is integrated into task network models and each task/subtask is assigned to an operator. Operators, in turn, have properties specific to their role in the simulation and individual differences can be incorporated in the operator profile by specifying amount of military training, length of service, age, rank, time in position, and workload threshold (Hansberger & Barnette, 2005; Richardson, Mittrick, & Hanratty, 2016; Swoboda et al., 2005). Tasks within the model have preconditions that must be met to execute the task. When a task is executed, the state of both the environment and the operator change. Due to the design of the task network, certain subtasks can be completed concurrently (especially if multiple operators are present) as long as the operator's workload threshold has not been exceeded. Task network models have been used in many military and commercial applications to make predictions about performance under varying conditions (e.g., Bloechle & Schunk, 2003; Laughery et al., 2000; Schunk, 2000).

Our task network model was developed in the C3TRACE (Command, Control and Communication Techniques for Reliable Assessment of Concept Execution; Kilduff, Swoboda, & Barnette, 2005) task-network modeling environment to represent the relevant tasks and subtasks involved in approach and landing phases of flight for the C-17 aircraft. C3TRACE is a modeling environment in which tasks, transitions, and operators can all be represented in a network model. It is owned by the US Army Research Lab (ARL-HRED) and was developed by Micro Analysis & Design (acquired by Alion Science and Technology) (Plott, 2017). C3TRACE allows the modeler to encode the relevant task information flow and then uses a stochastic discrete event simulator (the simulation engine is Micro Saint Sharp (Bloechle & Schunk, 2003)) to output results of the simulation. The modeler can then evaluate various aspects of task performance such as operator workload, task execution time, etc. In particular, C3TRACE allows the modeler to define the magnitude of the workload components for Visual, Auditory, Cognitive, and Psychomotor (VACP) aspects of performance for each task/subtask. Tasks can also contain logic regarding execution time, "if/then" rules to dictate when tasks can be "released", and the capacity to modify environmental variables as needed to simulate task effects (i.e., adjustments to plane position). In the past, C3TRACE has been utilized in simulating high-level team interaction because of its ability to integrate multiple personnel and personnel groupings into a model that selects operators based on availability (workload-based) and task priority. Furthermore, personnel characteristics can be modified to better reflect operator experience (i.e., education level, age, rank, time in position, workload threshold, etc.) that in turn can influence task performance (Cosenzo, Kilduff, & Swoboda, 2005).

Model Development

Approach and landing tasks and pilot and co-pilot interactions were developed based on an existing analysis of standard procedures and through discussions with two experienced C-17 pilots. The model was divided into two tasks: approach and landing as defined in the procedures. Each task was composed of several subtasks that had to be performed in a certain order, although some subtasks could be done concurrently as they required either the pilot or co-pilot to perform them (see Figure 1).

Approach and landing both have strong monitoring components (see Figure 2) as the pilot and co-pilot must maintain basic airplane operations such as keeping the plane level and slowly descending in altitude as the plane approaches the runway while simultaneously performing the necessary subtasks to ensure a safe landing (i.e., setting and checking altimeters, doing approach and landing checklists, setting the flaps, verifying glideslope, lowering the landing gear, etc.). The task analysis also indicated another monitoring task that could potentially alter the plane's course if a threat was detected and a corresponding set of subtasks needed to be performed if that occurred. All monitoring subtasks were implemented in the model as concurrently occurring during the main approach and landing subtasks. Therefore, the operator's attention had to be switched between the main task and the monitoring components.

Several environmental variables were included in the model to simulate the plane flying and descending. Those environmental variables were controlled by a "dummy" operator that continuously updates the plane's state variables both in response to the pilot/co-pilot interaction and by a basic linear drift model (see Figure 2). As the model runs, the plane gradually descends to the runway and the speed of descent (both X and Y direction) is modulated by variables such as flap settings.

The task analysis informed the model's timing of each subtask. C3TRACE allows the modeler to specify the mean and standard deviation of all timing intervals. For simplicity, the mean for each procedure was set to an estimate derived from the expert task analysis combined with input from the experienced pilots. A standard deviation of 10% was introduced to these estimates to add some stochasticity to the model's results. This value was used as a stand in and may change with future work; however, it does not affect the comparisons of the models discussed below. As per the task analysis, each subtask was assigned an operator or operator group (if either the pilot or co-pilot could perform the task). The task analysis also provided us with a breakdown of which VACP components were utilized in each subtask and those were set accordingly to simulate the workload associated with each subtask. Certain subtasks also altered state variables (i.e., flaps).

C3TRACE allows the starting conditions to be modified for each model run (i.e., the starting altitude of the plane and its descent rate) which can be utilized to produce predictions about when certain milestones will be reached during approach and landing (i.e., flaps are set, runway reached, checklists accomplished). These predictions can then be compared to data collected from real C-17 landings to verify the model's validity.

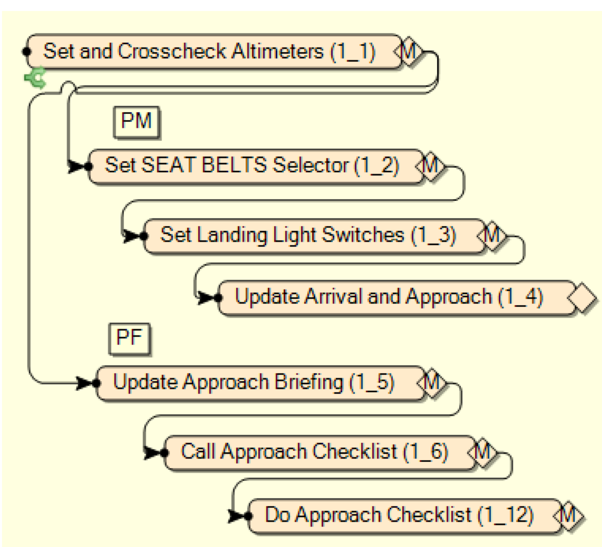


Figure 1: A sample set of subtasks required for approach. PM and PF indicate which operator typically does those tasks in order (PM: Pilot Monitoring, PF: Pilot Flying).

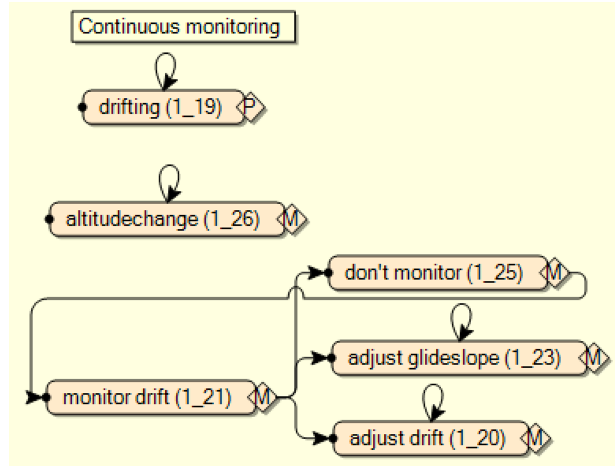


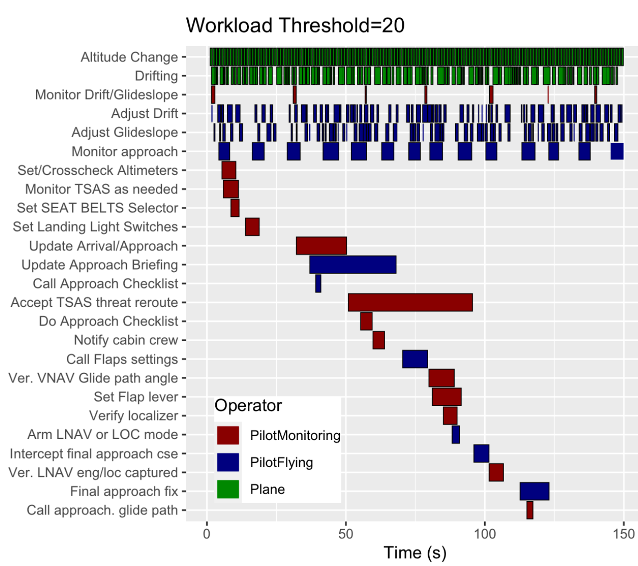
Figure 2: Snapshot of one monitoring component of the model. The *drifting* and *altitudechange* tasks are continuously performed by a "dummy" operator that updates the plane's position. The monitoring loop below involves the pilot or copilot making adjustments to the plane as needed to keep it on course.

Fatigue Modulation

As an initial approach to modifying performance on this task and to simulate fatigue, we utilized the workload threshold parameter that can be set for each operator. The scheduler in C3TRACE assigns tasks to operators as long as (1) all preconditions for a given task are met and (2) the operator's workload threshold is not exceeded by the currently running tasks. With the inclusion of the monitoring tasks in this model, it is very possible for the pilot or co-pilot to be in the process of monitoring some state variable and adjusting it while attempting to perform the necessary approach and landing subtasks. In instances where the VACP workload is high for a given subtask (i.e., visually inspecting a dial while reporting the reading and adjusting something else), the monitoring component may pose some interference especially if the operator's current workload threshold is lowered (i.e., due to fatigue).

The effects of fatigue manifest themselves in this model by (1) reducing how many simultaneous tasks can be accomplished, (2) when those tasks are scheduled, and (3) how long those tasks will take to complete. This has further implications for important state variables such as deviation from the ideal glideslope as monitoring tasks may be delayed by other tasks. Figure 3 depicts the task timeline showing the various subtasks as they occur during model execution during the first 150s of approach and landing (shortened to fit within paper margins) under two settings of workload threshold for the operators (both operators' workload threshold is set to the same amount, either 20 or 8). Of note is that as the workload threshold is reduced, the frequency with which monitoring and adjusting takes place diminishes (see Adjust Drift and Adjust Glideslope tasks listed in Figure 3). Furthermore, other subtasks are more staggered in their execution, prolonging the time to complete the required steps, as shown in the bottom graph where the bottom four subtasks are not even scheduled before 150s into the approach and landing procedure. Note that the number of simultaneous tasks that can execute is a function of both the workload threshold and the specific VACP components required for each task, so an exact number of simultaneous tasks will vary throughout model execution, but lower workload threshold will necessarily reduce the number of simultaneous tasks that the model can execute. The modification of workload threshold for operators is a good first approximation for modeling the deleterious effects fatigue has on performance.

We can inform the setting of the workload threshold by using fatigue estimates from biomathematical models of fatigue, in this case from the SAFTE model, and scaling the workload accordingly. Work is ongoing to determine the best way to do the scaling so as to produce changes in performance commensurate to those seen in human data. The output from the SAFTE model typically produces a performance effectiveness score on a scale of 0-100% by using sleep history (Hursh, et. al., 2004). In operational settings, performance effectiveness values higher than 77.5% indicate an alert individual, values between 70 and 77.5% indicate a moderately fatigued individual, and values below 70% indicate high fatigue and serious risk in continuing operating. In the approach and landing model described, a workload threshold setting of 20 would correspond to a relatively rested individual, whereas a setting of 8 would correspond to serious degradations in performance.



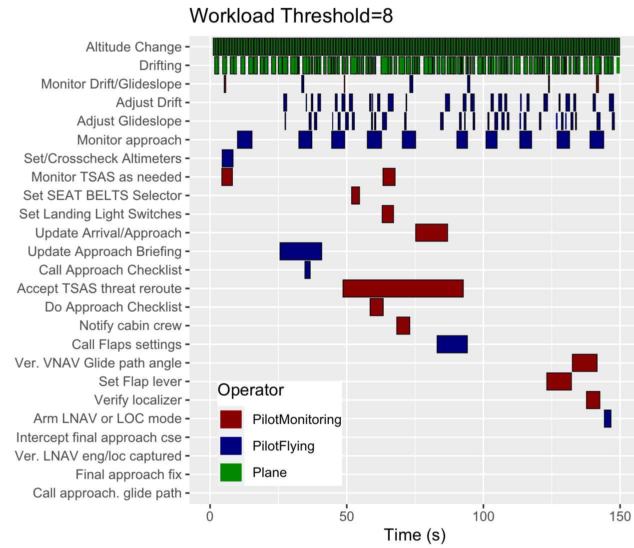


Figure 3: Task Timeline with different settings of operator workload threshold.

Model Results

The model was run 100 times using several settings of Workload Threshold for the two pilots. Preliminary results indicate differences in when important components of approach and landing procedures get executed (i.e., flaps deployed, speed brake set, gear lowered). In particular, lower levels of workload threshold resulted in significant delays and more variability in the timing of these subtasks (see Figure 4). In addition, there was an increase in the amount of drift observed throughout the model run as the operators made less adjustments to the plane (recall Figure 3's adjustment subtasks which are much more sparse in the WT=8 case).

There are many other diagnostic variables that we can observe in the output from a model run in C3TRACE which can be compared to real world landing data. Future work will integrate more of these variables.

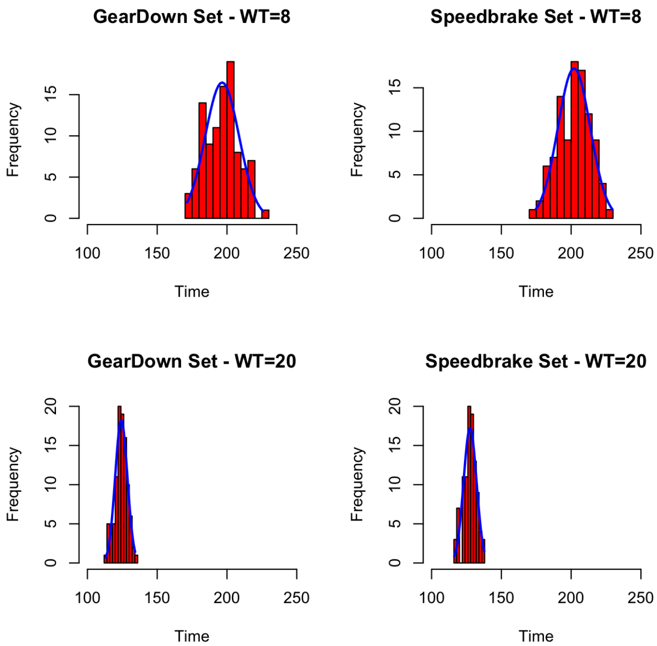


Figure 4: Distribution in timing of when gear is set down and when speed brake is set for two settings of workload threshold (100 model runs).

Discussion

We have developed an initial model integrating fatigue and a task network model of C-17 approach and landing operations. Currently, we modulate workload thresholds within the task network model with individualized fatigue estimates from the SAFTE model. SAFTE model estimates are derived from sleep estimates for individual operators. As a follow-on effort, we plan to validate the integrated model by fitting the predictions to performance metrics from actual C-17 flight data from an operational study. Sleep estimates will be derived from actigraph watches worn by pilots and co-pilots to generate fatigue estimates through SAFTE. The integrated model will allow us to identify specific performance degradations in the C-17 environment. This information can be used to develop more effective FRM programs and systems that link fatigue estimates to actual safety outcomes, a feature that is currently lacking in most FRM implementations (Dawson et al., 2016; Gander et al., 2017).

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