# A Modeling and Simulation Approach to Non-Line-of-Sight Launch System (NLOS-LS) Control Cell (CC) Crew Performance Analysis

1. **Introduction.** Evaluation of the warfighter's performance and workload levels while performing new operational tasks with developmental systems, under varying conditions, is difficult. Developing new tactics, techniques, and procedures (TTP), ensuring proper and supportable process sequencing, capturing live timing data, and conducting research on how the environment impacts Soldier performance makes this a time consuming and costly task. Emerging Future Combat Systems (FCS) program technologies require Soldiers to perform increased numbers of tasks with greater efficiency. The goal is to provide a level of analysis that can determine the effects of environmental conditions, such as battle fatigue, on cognitive battle command and physical performance. To address this need, the Training and Doctrine Command (TRADOC) Analysis Center-White Sands Missile Range (TRAC-WSMR) and Army Research Laboratory-Human Research and Engineering Directorate (ARL-HRED) have worked with the Modeling Architecture for Technology Research and Experimentation (MATREX) Human Centered – Network Enabled Battle Command (HC-NEBC) team to develop a representation of the NLOS-LS control cell in the Command Control and Communications Human Performance Model (C3HPM). The C3HPM is a constructive discrete event simulation that models human performance and human behavior in real-time. The C3HPM will allow the TRADOC Analysis Center (TRAC) to provide insights on the effects of nominal and stressed conditions likely to occur on the battlefield on NLOS-LS control cell operator task loading and workload performance. The objective of the C3HPM modeling and simulation effort is to analyze the maximum number of fire missions the control cell could perform in a given time period considering human performance limitations. In addition to this, the C3HPM's ability to dynamically alter warfighter performance based on stress conditions such as heat, cold, fatigue from continuous operations, vehicle motion, and environmental noise are used to further define the control cell operator's performance envelope. Early results of the C3HPM were utilized by TRAC to assist in the design of live test events for identifying the human performance characteristics in 2008. The results of these live events were then in turn used to improve the fidelity of NLOS-LS control cell factors portrayed in the C3HPM. The results of this analysis will support a NLOS-LS control cell Milestone C decision in fiscal year (FY) 10 to equip Soldiers with this state-of-the-art technology. This paper details the application of the C3HPM to analyze NLOS-LS control cell operator workload over time and provides insights into the performance envelope of Soldiers performing these tasks.

2. **C3HPM.**

a. **Model Description**. The C3HPM is a simulation that executes behavior models of individual warfighters. Each instance of the C3HPM can simulate the behavior of multiple warfighters, depending on the complexity of the behavior models. Multiple C3HPM can be used in the same simulation to increase the number of simulated warfighters. The C3HPM is envisioned for pre- and post-Force Development Test and/or Experiment (FDT/E) support.

(1) *Warfighter Roles and Services.* The C3HPM uses the Web Ontology Language for Services (OWL-S) model to identify the warfighters' roles and associate these roles to

one or more warfighters. Each warfighter may have one or more assigned roles. Individual services specified in a role have assigned priorities that determine execution order when multiple services need to be performed. Higher priority services preempt lower priority services and complete before lower priority tasks are allowed to run. In this manner, the warfighter performs only one task at a time and ensures that the next task to be performed is the most important task. Services can be placed in a "wait state," to be triggered by some specific event, freeing the warfighter to perform other activities or other service steps of the same task. Each C3HPM warfighter may be associated with a One Semi-Automated Force (OneSAF) platform, allowing the warfighter to execute battle command tasks for the platform and move through the battlefield.

(2) *Log File.* The C3HPM logs the activities of each simulated warfighter. The log includes the task being performed, as well as the workload associated with that task, each time the task changes. The log contains all warfighter messages sent or received. This data allows the construction of timelines for the execution of mission threads. In addition, it enables the identification of the information on which decisions were based, assisting in determining the warfighters' level of situation awareness.

(3) *Interface Layer.* The C3HPM interface layer accepts command and control (C2) messages, places the message data into a C2 message database, and triggers the corresponding behavior defined by the role of the addressed warfighter. The C3HPM interface layer also performs role instance management to initiate copies of a task network for different instances of the same warfighter role and to prioritize tasks to ensure tasks associated with the service are queued in the correct order.

(4) *Improved Performance Research Integration Tool (IMPRINT).* IMPRINT is the underlying driver for C3HPM. IMPRINT provides the means to execute time-defined task networks in a discrete-event simulation on behalf of multiple entities and associate the workload of each task to the appropriate entity. The C3HPM downloads IMPRINT task networks that are translated from the OWL-S behavior model to instantiate a task network for each service of each role. The C3HPM synchronizes the task execution with simulation time and executes tasks on behalf of the warfighter in accordance with the task execution times specified in the model. The task networks are initiated by the C3HPM interface layer on receipt of a C2 message addressed to a particular warfighter. Data associated with the C2 message is stored within a C2 message database within the C3HPM. The C3HPM allows task networks within the IMPRINT discrete-event simulation to send queries to the C2 message database to find relevant C2 messages, as well as to evaluate the content of specific C2 messages to implement decision points in the task networks.

b. **Taxons and Stressors**. The C3HPM allows the setting of the environmental conditions (stressors) within which modeled role players must participate. The core stressors C3HPM supports are heat (which takes into account humidity), cold (which takes into account wind chill), noise level, MOPP level, and sleeplessness. These stressors impact the timeliness and/or accuracy that a role player performs a particular task. Each task performed by a role player is assigned taxons, which bins each task into categories of communication (oral or reading and writing), physical performance (fine or gross motor), visual processing, numerical processing, and cognitive processing.  Tasks can take on one or more of these taxons.  How stressors impact these taxons is displayed in Figure 1.

| | C3HPM Stressors | | | | |
|---|---|---|---|---|---|
| **Taxons** | **MOPP Level** | **Temperature (Heat)** | **Temperature (Cold)** | **Noise** | **Sleepless Hours** |
| **Visual** | T | A | T | | |
| **Numerical** | | A | | | TA |
| **Cognitive** | | A | | | TA |
| **Fine Motor Discrete** | T | A | T | | |
| **Fine Motor Continuous** | | | | | |
| **Gross Motor Light** | T | | T | | |
| **Gross Motor Heavy** | | | | | |
| **Communication (read/write)** | | A | | | |
| **Communication (oral)** | T | A | | A | |

Stressors impact taxons by *increasing the time* to complete the task (T) or by *decreasing the accuracy* of which the task is performed (A).

**Figure 1.  C3HPM Stressors and Taxons.**

3.  **Initial Processes Modeled.**  ARL captured timing data on the NLOS-LS control cell fire mission procedures during an NLOS-LS control cell exercise, held at the Fort Sill Fires Battle Lab in July 2007, and documented the specific steps performed by each crewmember during the fire missions presented in each scenario run.  In addition to timing data, ARL assigned a visual, auditory, cognitive, and psychomotor (VACP) workload for each task performed by an NLOS-LS control cell crewmember.  This timing and workload data supported the development of the currently modeled functionality of the NLOS-LS control cell in the C3HPM.  The development of NLOS-LS control cell processes in the C3HPM allows TRAC to gain insights to which environmental stressors actually impact the control cell operators over the spectrum of military operations.  Figure 2 displays the resulting call for fire (fire mission) process captured by ARL.

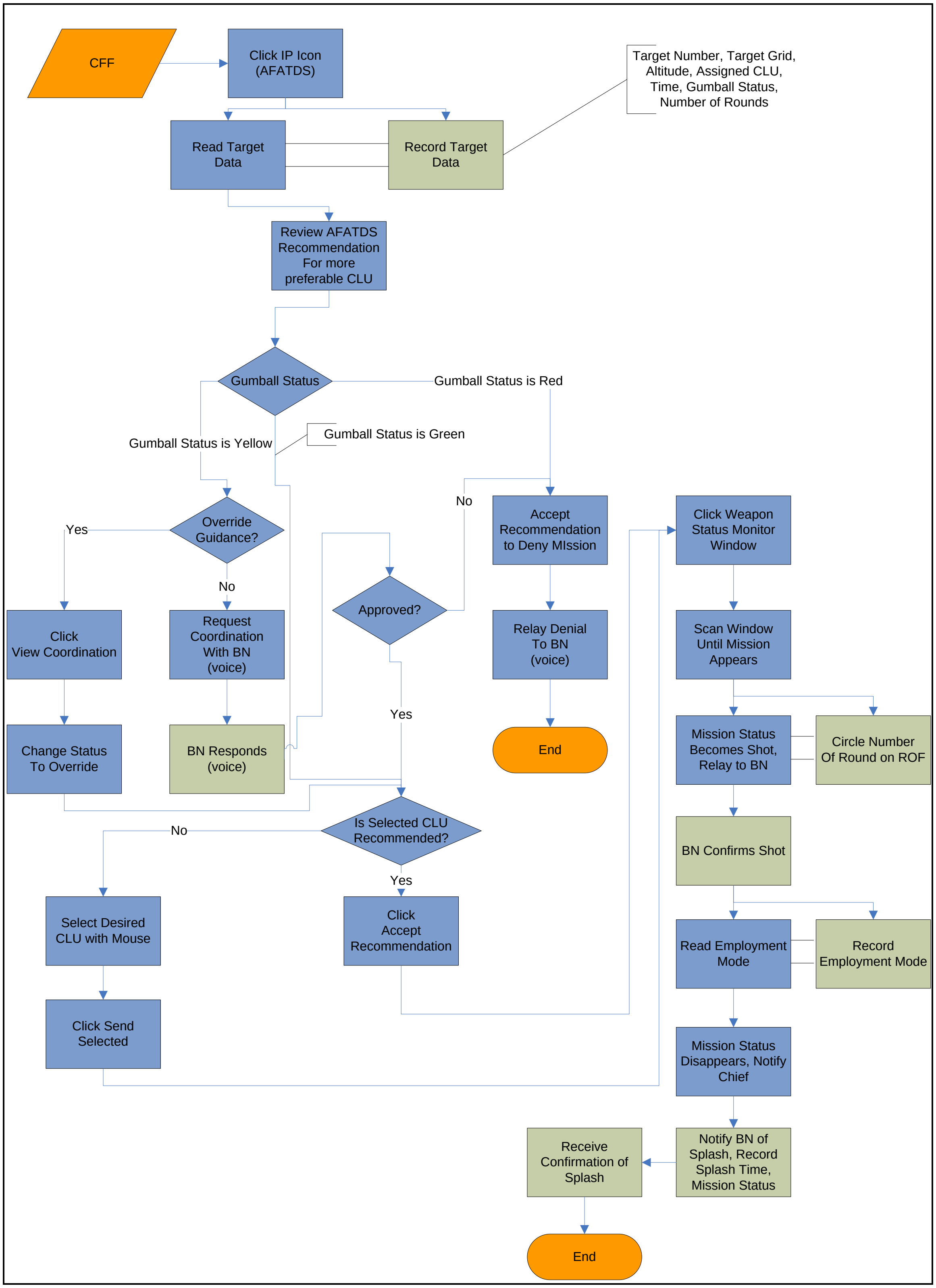


**Figure 2. Implemented C3HPM Call for Fire Process.**

4. **Initial Run Matrix.** The initial C3HPM run matrix took into account eight stress factors to determine their impacts on fire mission processing time, processing accuracy, and servicing completion. The eight factors used in the development of the run matrix were fire mission workload (missions/hour), temperature (°F), wind (knots), humidity (percent), sleeplessness (hours), noise (dB), mission oriented protective posture (MOPP) (level), and continuous movement exposure (hours). Table 1 displays the levels of each stress factor investigated for the initial C3HPM runs.

**Table 1. C3HPM Run Matrix Stress Factors and Levels.**

| Stress Factors | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | Level 6 | Level 7 |
|---|---|---|---|---|---|---|---|
| Workload (missions/hr) | 5 | 15 | 22 | 30 | 37 | NA | NA |
| Temperature (°F) | -40+ | -21 to -4 | 15 to 32 | 33 to 93 | 94 to 102 | 103 to 114 | 114+ |
| Wind (knots) | 0-10 | 21-30 | 31-40 | 50+ | NA | NA | NA |
| Humidity (%) | 21-30 | 41-50 | 51-60 | 61-70 | NA | NA | NA |
| Sleeplessness (hr) | 0-24 | 25-47 | 48-71 | 72-95 | 96+ | NA | NA |
| Noise (dB) | 50-60 | 70-80 | NA | NA | NA | NA | NA |
| MOPP (level) | 0 | 3 | 4 | NA | NA | NA | NA |
| Movement (hr) | 0 | 1 | 2 | 3 | 4 | NA | NA |

a. **Run Matrix Reduction – Part I.** The initial C3HPM run matrix, if every stress factor and level combination were run in C3HPM, generates 84,000 test cases and is counter productive if all cases are executed. From historical data gathered on weather from past C3HPM development, the following facts helped to reduce the number of test cases. Humidity only affects high temperatures, wind only affects cold temperatures, and humidity and wind does not affect warm temperatures. Based on these weather facts, the full eight-factor experimental design was divided into three groups based on temperature, humidity, and wind. One experimental design focused on high temperature and humidity (excluding wind), producing a seven-factor design of 9,000 test cases. The second experimental design focused on low temperature and wind (excluding humidity), producing another seven-factor design of 9,000 test cases. The last experimental design focuses on warm temperature (excluding humidity and wind), producing a six-factor design of 750 test cases. Tables 2 through 4 show the stress factors by level for each one of these grouped experimental designs, respectively.

**Table 2. High Temperature and Humidity Experimental Design.**

| Stress Factors | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|
| Workload (missions/hr) | 5 | 15 | 22 | 30 | 37 |
| Temperature (°F) | 94 to 102 | 103 to 114 | 114+ | NA | NA |
| Humidity (%) | 21-30 | 41-50 | 51-60 | 61-70 | NA |
| Sleeplessness (hr) | 0-24 | 25-47 | 48-71 | 72-95 | 96+ |
| Noise (dB) | 50-60 | 70-80 | NA | NA | NA |
| MOPP (level) | 0 | 3 | 4 | NA | NA |
| Movement (hr) | 0 | 1 | 2 | 3 | 4 |

**Table 3. Low Temperature and Wind Experimental Design.**

| Stress Factors | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|
| Workload (missions/hr) | 5 | 15 | 22 | 30 | 37 |
| Temperature (°F) | -40+ | -21 to -4 | 15 to 32 | NA | NA |
| Wind (knots) | 0-10 | 21-30 | 31-40 | 50+ | NA |
| Sleeplessness (hr) | 0-24 | 25-47 | 48-71 | 72-95 | 96+ |
| Noise (dB) | 50-60 | 70-80 | NA | NA | NA |
| MOPP (level) | 0 | 3 | 4 | NA | NA |
| Movement (hr) | 0 | 1 | 2 | 3 | 4 |

**Table 4. Warm Temperature Experimental Design.**

| Stress Factors | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|---|
| Workload (missions/hr) | 5 | 15 | 22 | 30 | 37 |
| Temperature (°F) | 33 to 93 | NA | NA | NA | NA |
| Sleeplessness (hr) | 0-24 | 25-47 | 48-71 | 72-95 | 96+ |
| Noise (dB) | 50-60 | 70-80 | NA | NA | NA |
| MOPP (level) | 0 | 3 | 4 | NA | NA |
| Movement (hr) | 0 | 1 | 2 | 3 | 4 |

b. **Run Matrix Reduction – Part II.** The three experimental design groupings described in paragraph 4a produced 18,750 test cases, which were still too many to run with limited time and resources. To further reduce the number of test cases, the three run matrices were subjected to the Nearly-Orthogonal Latin Hypercube (NOLH) sampling method. NOLH ensures that each factor level is fully covered with only n experiment runs instead on $n^m$ experiment runs. By using the NOLH sampling method, the three experimental design weather sets can be sufficiently analyzed with a minimum of 33 test cases for each weather set. To allow for greater confidence of statistical analyses performed after the C3HPM runs, at least 65 test cases per weather set were executed. This resulted in a minimum of 195 test cases for the initial set of C3HPM runs. Additional test cases were run to fill in gaps from the NOLH sampling method. The final number of test cases for the initial set of C3HPM runs came to 259.

5. **Initial Results.**

a. By doing a comparative analysis on the initial set of 259 test cases, the stress factors that have a main effect on fire mission processing time are the environmental condition of heat and humidity, fire mission workload, and ambient noise. Heat and humidity conditions of 103° to 114 °F with a relative humidity above 61 percent and of temperatures greater than 114 °F with a relative humidity around 51 percent had the most impact on fire mission processing times. The combination of fire mission workload and MOPP level also showed effects on fire mission processing time. Effects were significant when the fire mission workload was greater than 20 missions per hour in MOPP 4 or when the fire mission workload exceeded 30 missions per hour in MOPP 3. When ambient noise levels are between 70 and 80 dB and control cell operators are continuously exposed to movement for more than three hours, fire mission processing times increase. Figure 3 summarizes the stressors that effect fire mission processing time.

- **Main Stressor Effects on Fire Mission Processing Time.**
  - Environmental Condition (Heat & Humidity).
    - 103 - 114° F with > 61 % relative humidity.
    - > 114° F with 51% relative humidity.
  - Workload (missions per hour).
  - Ambient Noise.
- **Stressor Interaction Effects on Fire Mission Processing.**
  - Workload & MOPP.
    - >20 fire missions per hour in MOPP 4.
    - >30 fire missions per hour in MOPP 3.
  - Ambient Noise and Movement Exposure.
    - 70 - 80 dB with > 3 hours of movement exposure.

**Figure 3. Main and Interactive Stress Factors on Fire Missions.**

b. The effects of sleeplessness on fire mission processing were very minimal due to the fact that the majority of the fire mission processing tasks were not cognitive tasks or did not require the operator to perform some sort of numerical computation. ARL representatives have done literature searches on potential impacts of sleeplessness on visual, fine motor, and/or communications taxons that C3HPM supports. New algorithms, based on this literature research, will need to be developed for implementation into C3HPM, which is a much lengthier process than the time allowed for the SO1 FDT/E analysis.

6. **Post-FDT/E Runs.**

a. To gauge the accuracy of the C3HPM in relation to the fire mission processing conducted by a live NLOS-LS control cell, a representative slice of the simulation data that most-closely matched the FDT/E environmental conditions was compared against the live NLOS-LS control cell data that was collected during the FDT/E. The C3HPM conditions most representative of the live FDT/E environmental conditions were the non-applicability of heat, humidity, cold, and wind (implying that temperatures were in the "warm" temperature category), noise level in the 70-80 dB range, Soldiers in MOPP 0, Soldiers well-rested (meaning the last time Soldiers slept was between 0-24 hours), and continuous movement lasting no longer than 2 to 3 hours. Comparing this C3HPM data to that captured during the live FDT/E, it can be stated that there is no significant difference between the mean fire mission processing time collected on the live NLOS-LS control cell crew and the mean fire mission processing time generated by the simulated NLOS-LS control cell in C3HPM. Table 5 displays the comparative NLOS-LS control cell processing results between C3HPM and the FDT/E.

**Table 5. Comparison of CC Processing Times between C3HPM and FDT/E.**

| z-Test: Two Sample for Means | C3HPM | Live FDT/E |
|---|---|---|
| Mean Processing Time (Minutes) | 2.20 | 2.09 |
| Known Variance | 0.33 | 1.22 |
| Observations | 30 | 30 |
| Hypothesized Mean Difference | 0 | |
| z | 0.46 | |
| P(Z<=z) one-tail | 0.32 | |
| z Critical one-tail | 1.64 | |
| P(Z<=z) two-tail | 0.65 | |
| z Critical two-tail | 1.96 | |

b. The 259 Post-FDT/E C3HPM runs, that included the model updates, mirrored the same trends as discussed in paragraph 5 (Figure 3) on the main and interactive stress factors impacting NLOS-LS control cell fire mission processing.

7. **Additional C3HPM Results.**

a. **One-Man and Two-Man Crew Comparison.** A comparative analysis on fire mission processing times between a one-man and two-man NLOS-LS crew was also conducted, and a significant difference between the fire mission processing means was revealed. The one-man NLOS-LS control cell crew actually processed the fire missions faster than the two-man crew due to the elimination of communications tasks between the crew chief and the Advanced Field Artillery Tactical Data System (AFATDS) operator (i.e., the reading and repeating of fire mission data). The one-man crew, consisting of an

AFATDS operator, simply copies the information from the AFATDS screen to the record of fire and continues with the fire mission processing. This insight, which appears to be counter-intuitive, could have force structure ramifications on the NLOS-LS platoon manning requirements for sustaining continuous operations in an FCS IBCT. Table 6 displays the comparative fire mission processing times between the one-man and two-man NLOS-LS control cell crews.

**Table 6. Comparison of CC Processing Times between 1 and 2 Member Crews.**

| z-Test: Two Sample for Means | 2 Crew Members | 1 Crew Member |
|---|---|---|
| Mean Processing Time (Minutes) | 2.20 | 1.76 |
| Known Variance | 0.33 | 0.52 |
| Observations | 30 | 30 |
| Hypothesized Mean Difference | 0 | |
| z | 2.65 | |
| P(Z<=z) one-tail | 0.0040 | |
| z Critical one-tail | 1.64 | |
| P(Z<=z) two-tail | 0.0080 | |
| z Critical two-tail | 1.96 | |

b. **Augmented and Baseline Comparison.** The comparison between the C3HPM augmented case (post-FDT/E) versus the baseline case (pre-FDT/E) shows a significant difference in the mean NLOS-LS control cell fire mission processing times. Intuitively, the mean fire mission processing times should be the same for the two cases. The augmented C3HPM fire missions, however, were taking longer to process at the NLOS-LS control cell due to the task processing added for the battalion fire direction center (FDC). ARL representatives checked the C3HPM and the augmented data. The reason for the increased processing time in the augmented runs was attributed to the battalion FDC model. In the C3HPM, tasks are based on receipt of messages. There is currently a 1:1 relationship with messages, which also dictates task priority. Communications between the NLOS-LS control cell and the battalion FDC all take place through one message: Free Text. When the battalion FDC model receives the Free Text message, it decides how to proceed based on the content of the message. The NLOS-LS control cell must wait on a response from the battalion FDC to complete fire missions requiring airspace coordination. The crew interactions and fire mission processing at the battalion FDC were causing the increase in the processing time at the control cell. This slide displays the comparison of mean NLOS-LS control cell fire mission processing times between pre-FDT/E and post-FDT/E runs in C3HPM.

**Table 7. Comparison of CC Processing Times between Post- and Pre-FDT/E.**

| z-Test: Two Sample for Means | C3HPM (Post-FDT/E) | C3HPM (Pre-FDT/E) |
|---|---|---|
| Mean Processing Time (Minutes) | 2.20 | 1.70 |
| Known Variance | 0.33 | 0.28 |
| Observations | 30 | 30 |
| Hypothesized Mean Difference | 0 | |
| z | 3.46 | |
| P(Z<=z) one-tail | 0.00027 | |
| z Critical one-tail | 1.64 | |
| P(Z<=z) two-tail | 0.00054 | |
| z Critical two-tail | 1.96 | |

8. **Follow-on Work.** Fire mission workload on the NLOS-LS control cell will not be the main focus, even though it affects processing time when arriving in bunches, during future C3HPM runs. Tasks and activities, such as conducting maintenance, reload and refueling operations, eating, sleeping, and/or going to meetings and briefings, requiring NLOS-LS control cell crew involvement outside the control cell and the impacts these tasks and activities have on control cell operations and fire mission processing will be the main focus. The development of a C3HPM environment that consists of a 24-hour (or multi-day) slice from a Fires Battle Lab fire mission data set, represents nominal temperature and weather conditions, and produces time or event-based injects that require NLOS-LS crewmembers to perform tasks and activities outside of control cell fire mission operations. These injects will be based on the AETF Fires Battalion battle rhythm used for the FY08 FDT/E. This will establish a new baseline from which stressors of interest, such as battle fatigue, can be adjusted to determine how the overall fire mission timeliness and accuracy are impacted. Tasks and activities outside of the control cell will not be required to have all the steps modeled. For example, if the inject states that maintenance will be conducted at 0600 hours, then one control cell crew member will leave the control cell for approximately 30 minutes at this time. If fire missions start arriving while conducting maintenance, then the NLOS-LS crewmember will go back to the control cell and finish the required maintenance when the all clear is given. As data is collected in the field on particular tasks, the fidelity of these modeled tasks can be increased. As part of the FY09 planning for MATREX, ARL has proposed conducting longer runs (day or multi-day) that will join the NLOS-LS in C3HPM with a Semi-Automated Force (SAF) and engineering level models that represent the AFATDS and Precision Attack Munition (PAM). This will provide a complete representation of an operational area in simulation, where simulated detections may generate fire missions for the NLOS-LS control cell to process.

9. **References.**

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10. **Glossary**.

a. **Visual Taxon.** Requires using the eyes to identify or separate targets or objects (e.g., seeing something move and then recognizing it as an enemy tank).

b. **Numerical Taxon.** Requires performing arithmetical or mathematical calculations (e.g., measuring an azimuth on a map with a protractor or estimating the distance between two points on a map).

c. **Cognitive Taxon (Problem Solving and Decision Making)**. Requires processing information mentally and reaching a conclusion (e.g., locating a fault in an electrical system after troubleshooting or selecting the best firing position for a machine gun).

d. **Fine Motor Discrete Taxon.** Requires performing a set of distinct actions in a predetermined sequence mainly involving movement of the hands, arms, or feet with little physical effort (e.g., assembly and disassembly of the M-16 rifle or starting the engine of a truck).

e. **Fine Motor Continuous Taxon.** Requires uninterrupted performance of an action needed to keep a system on a desired path or in a specific location (e.g., driving a vehicle or tracking a moving target).

f. **Gross Motor Heavy Taxon.** Requires expending extensive physical effort or exertion to perform an action (e.g., lifting an artillery round or loosening a very tight bolt with a wrench).

g. **Gross Motor Light Taxon.** Requires moving the entire body (i.e., not just the hands) to perform an action without expending extensive physical effort (e.g., getting into a prone firing position or evacuating a tank).

h. **Communications (Read and Write) Taxon.** Requires either reading text or numbers that are written somewhere or writing text or numbers that can be read (e.g., reading a preventive maintenance checklist for a vehicle or writing a letter home).

i. **Communications (Oral) Taxon.** Requires either talking or listening to another person (e.g., giving a situation report by radio or receiving a password from someone while on guard duty).

11. **Acronyms.**

| | |
|---|---|
| AETF | Army Evaluation Task Force |
| AFATDS | Advanced Field Artillery Tactical Data System |
| ARL | Army Research Laboratory |
| C2 | command and control |
| C3HPM | Command, Control, Communications Human Performance Model |
| CC | control cell |
| FCS | Future Combat System |
| FDC | Fire Direction Center |
| FDT/E | Force Development Test and/or Experiment |
| FFID | Future Forces Integration Directorate |
| HC-NEBC | Human Centered – Network Enabled Battle Command |
| HRED | Human Research and Engineering Directorate |
| IMPRINT | Improved Performance Research Integration Tool |
| MATREX | Modeling Architecture for Technology Research and Experimentation |
| MOPP | mission-oriented protective posture |
| NLOS-LS | Non-Line-of-Sight Launch System |
| NOLH | Nearly-Orthogonal Latin Hypercube |
| OneSAF | One Semi-Automated Force |
| OWL-S | Web Ontology Language for Services |
| SAF | Semi-Automated Force |
| SO1 | Spin Out 1 |
| ST | special text |
| TRAC | TRADOC Analysis Center |
| TRADOC | Training and Doctrine Command |
| TTP | tactics, techniques, and procedures |
| VACP | visual, auditory, cognitive, and psychomotor |
| WSMR | White Sands Missile Range |