MODELING WEAPONS CREW PERFORMANCE

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The U. S. Army Research Institute for the Behavioral and Social Sciences is currently conducting a research program to develop a method and obtain the data required to evaluate the ability of weapons crews to maintain their performance over the course of extended, continuous operations. The basic approach involves developing a computer-based model which will meld modifications of selected industrial "methods engineering" techniques with appropriate human performance data in order to predict crew performance without the need to create, train and measure each crew structure alternative in simulated battle conditions.

The approach involves creating a computer-based model which will simulate a crew performing all, or selected portions of, the tasks required to operate the system being studied. The model operates with inputs representing tasks and task times and, when such data become available, it will contain tables defining the performance decrements which are expected to occur during extended operations. Two portions of the project have been completed to date. A crew simulation model has been developed and a task and task time library has been compiled for M109A1 howitzer sections (1, 2). Progress has also been made on a literature review being conducted to determine what data are available for use in developing performance decrement tables.

In future battles howitzer crews will likely be required to operate around the clock for periods of up to eight days. During these periods crews will move as often as 6 to 12 times a day and fire at rates varying from 125 to 500 rounds per 24 hour period. Figure 1 shows a fire rate by day of battle estimate which has been used in past Field Artillery School presentations of a first battle in Europe scenario. In estimating the number of moves, it was assumed that on the average a howitzer would move once for every 50 rounds fired, as the result of repositioning required either because of changes in the location of the Forward Edge of the Battle Area (FEBA) or because of relocations to avoid counterfire. In the projected scenario, the section will fire 2060 rounds and move 41 times during

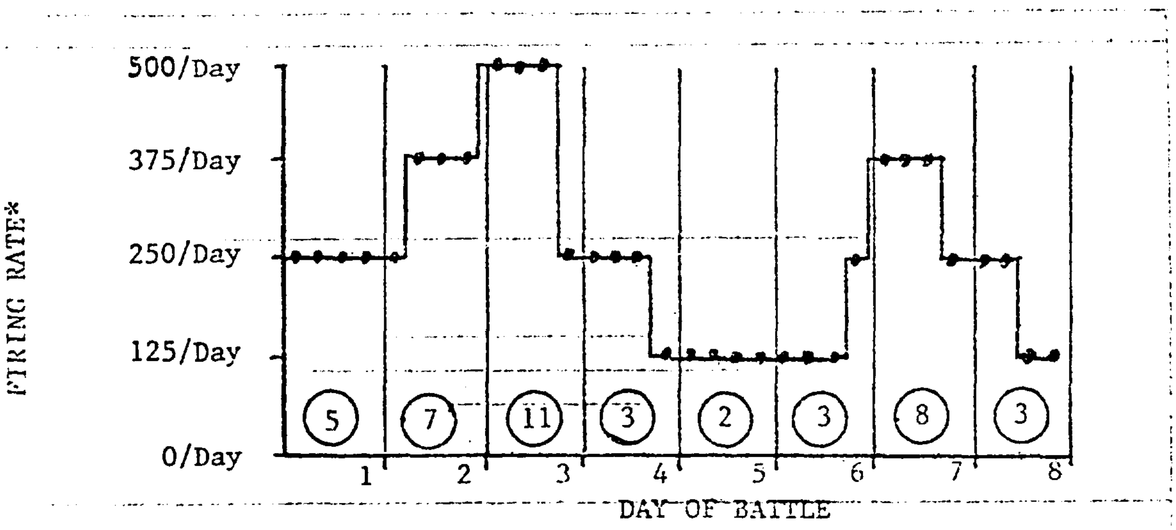

Figure 1. Estimated firing rate per six hour period and moves per day for a potential first battle in Europe scenario.

*In rounds per howitzer per day. (XX) Moves per day.

the eight day battle. Can a ten man howitzer crew do this and if so, how should the crew workload be assigned in order to best accomplish it? These are the questions that the research program, reported here in part, seeks to answer.

ASSUMPTIONS UNDERLYING THE MODEL

In order to model crew structures and analyze a crew's ability to withstand the demands of the extended, continuous battle we found it necessary to address first the various kinds of tasks which a howitzer crew must perform. We considered three parameters: the type of task, the purpose of the task and the impact of the task on the section's resources. The classification scheme describes tasks as discrete or level-of-effort, fighting or support, and expending or replenishing. Replenishment tasks either replenish resources or reduce risks.

A discrete task is one that has a start and stop point and is limited by the task itself in terms of the number of persons who can work on it. An example is selecting a fuze and putting it on the projectile. Such tasks are variable in the time it takes to perform them and when the task is over the crew member is free to go on to another task. If discrete tasks are performed slowly, or if task sequences are performed slowly because of poor task sequence arrangement, the affected crew members are not free to go on to other tasks. Discrete tasks can be performed more rapidly with effective training and they lend themselves to rearrangement to improve the crew effectiveness. Level-of-effort (LOE) is applied to all tasks which are not considered as discrete. This category includes such activities as standing guard, preparing defensive positions and sleeping.

The reason for the discrete vs level-of-effort task distinction is to simplify the model. The tasks we have classified as discrete lend themselves to analysis by the modeling approach we have adopted. Discrete tasks can be assigned in different orders and to different crew members; they can be evaluated individually to determine the effects of various parameters, such as training or fatigue; and they are all involved in crew processes in which the quicker they are properly performed the better the crew performs. LOE tasks are a scheduling problem rather than a crew structure problem. LOE tasks tend to take longer to perform, do not lend themselves to a "quicker is better, so we should train to perform them faster" approach and usually have little or no room for being speeded up by a more efficient method.

In developing a rationale for our model we have also considered which of two purposes a task serves. Fighting tasks include all those tasks which must be performed when a howitzer section is emplaced, fired, or march-ordered (e.g., loading a projectile). Support tasks are all the tasks not classified as fighting tasks. Support tasks are performed in order to maintain the ability of the section to continue to perform its fighting tasks (e.g., ammunition resupply).

Finally, tasks may be considered in terms of their impact on the section's resources. The fighting tasks all expend resources, e.g., firing uses ammunition, moving uses fuel and men get tired. Support tasks, on the other hand, are intended to restore or conserve resources; hence, they either replenish resources expended as the section moves and fires, or they reduce the risk that the section will be placed in a position where its resources will be unnecessarily expended.

The task categories provide a basis for considering the tasks of a howitzer crew in a series of steps rather than in a single stage. Thus, in modeling a crew, and in actual operations, deciding if a crew can perform adequately can be answered by determining first if they fight the howitzer adequately and then if they have time to perform the necessary support tasks. Once this baseline has been established, performance during extended, continuous operations can then be considered.

Three of the four task sequences involved in fighting a howitzer--emplacement, firing, and march-order--are composed almost entirely of discrete tasks. The fourth sequence, the in-transit phase, is composed mostly of LOE tasks. It is feasible, therefore, to model the set-up, firing and march-order sequences and evaluate how well different crew arrangements meet time standards for performing these phases. This approach makes speed of performance a measure of a crew's ability to perform the task sequences involved in fighting the section. (Errors are taken into account by their effects on speed. When errors are made, they must be corrected before proceeding, hence speed suffers.)

The number of persons not assigned to fighting duties determines the amount of time available for performing support functions. Judgments must be made concerning the priority of the various replenishment and risk reduction tasks in order to assign the available personnel most efficiently. How well a crew structure meets the support task requirements is then measured by matching the support task man-hour requirements to the man-hours the crew structure provides to attend to them.

A crew structure is adequate when it meets the time standards for fighting task sequences and provides enough man-hours for the required support tasks. Structures that do not fully meet these requirements become increasingly inadequate as a function of both the lack of adequate support man-hours and the additional time required to perform the fighting tasks. Selection between sub-optimal alternatives for actual operations is a problem that requires the kinds of data that the Crew Performance Model can provide.

The present standard crew operating procedure is defined in Technical Manual 9-2350-217-10N (3). The procedure indicates that ten men emplace a howitzer section, eight fire it, nine march-order it and either nine or ten men are in-transit as the section moves between locations. This operating procedure provides little manpower for assignment to support duties. For instance, when the gun is firing, only two persons are available for support duties. Thus, if a section were to remain in one location for an entire day, 48 man-hours (2 X 24) would be available for support duties. Since four hours sleep per man each day is a minimal support function, 40 of these 48 hours would be required just to provide the crew with minimal rest.

Table 1 is a list of support tasks classified as replenishment or risk reducing. The task times were obtained mostly from doctrine requirements and Field Artillery School documents. Table 1 shows that support requirements easily exceed 129 man-hours per day. Thus, the support tasks which must be performed if a howitzer section is operated around the clock and according to doctrine will almost certainly exceed the ability of the crew to perform them. For that reason Section Chiefs continually face a series of trade-offs: They must first decide how many people can be removed from the fighting tasks; they must then evaluate the situation and set priorities on the replenishment and risk reduction duties required to support the section and battery; finally they must schedule the available support manpower to perform the most essential support tasks.

Table 1

List of Replenishment and Risk Reducing Support Tasks and Selected Estimates of Performance Time

		Estimated Time in Man-Hours/Day
Replenishment Tasks		
a.	Replenish ammunition (500 rds)	16.0
b.	Replenish POL	1.0
c.	Non-scheduled maintenance	4.0
d.	Sleep	40.0
e.	Supply SGT duty	6.0
f.	Personal maintenance (chow, hygiene, body functions, weapons and gear)	4.0
g.	Identify and prepare new firing positions	12.0
Risk Reduction Tasks		
a.	Preventative maintenance	1.0
b.	Perimeter defense/early warning	20.0[1]
c.	Guard nuclear ammunition	5.0[2]
d.	Prepare supplementary positions	N/A
e.	Prepare latrines, sleep areas, etc.	N/A
f.	Improve positions	N/A
g.	Camouflage	N/A
h.	Screens	N/A
i.	Foxholes	N/A
j.	Crew-served weapon positions	N/A
Involuntary Downtime while Moving		20.0
Total of Estimates		129.0

[1]This assumes two guards at each of four stations with the battery operating as an eight-gun unit. If the battery were operating as two four-gun units, this figure would be 40.0.

[2]This would be 10 man-hours/day if the battery were operating as two four-gun units and both units had nuclear ammunition.

NOTE: N/A indicates time estimates for these tasks were not available.

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STRUCTURE OF THE CREW PERFORMANCE MODEL

The ARI Crew Performance Model was developed to assist the Section Chief--or the system developer if the system is not yet fielded--in answering such questions as how to structure a crew to deal effectively with both fighting and support functions under a variety of conditions. The modeling approach we use takes into account the tasks to be performed, the order of performance, the time it takes to perform each task, and the number of men doing those tasks. The model consists of a task library, an input program, and the software to handle that information.

The task library contains the tasks and subtasks which must be performed by the members of an M109A1 howitzer section. (A task library could be built for any system, provided the discrete tasks making up that system can be defined.) Each task is narrowly defined, has minimum, average, and maximum completion times, and takes into account any requisite or concurrent tasks. Each library entry also has a task type code, a probability of performance value and an indication of how the time data were obtained. The format for task library entries is shown in Figure 2, Part A. Entries were obtained from appropriate documentation, discussions with subject matter experts and videotapes of two III Corps howitzer crews in operation. For the latter, each crew emplaced their section, fired three rounds and march-ordered; this cycle was performed four times. Thus, our times are generally based on eight trials for emplacement and march-order tasks and 24 trials for firing tasks.

In order to use the model, the user--whether Section Chief or system developer--needs to specify the number of persons to which tasks will be assigned and then assign the tasks in the order each crew member will perform them. An example of an input sequence is shown in Part B of Figure 2. The main program then simulates the number of iterations specified and provides the output shown in Part C of Figure 2.

USING THE MODEL

The model has been used to determine the effects of various crew sizes/task assignments on the performance of howitzer sections. The base case is the crew size/task structure as presented in the TM. For variations of those structures, we deleted men and assigned their tasks to the remaining men in such a way that those crewmen who were not very busy tended to assume most of the tasks, particularly those which were logically consistent with their current positions. The results of several runs are shown in Figure 3. The figure shows completion times and percentages of crew member idle time for units of different sizes performing fighting task sequences. In the figure, completion time is expressed as a percentage of the median time the model calculated for a full ten man crew performing the task sequences according to the Technical Manual.

A TASK LIBRARY ENTRY

123 456 789 2.0 3.0 4.5 TT.PPP S
AN ILLUSTRATION OF A TASK SHOWING ALL VARIABLES

B CREW TASK/STRUCTURE INPUT

1	400	402	404	406	408	410	412	650	652	654
2	555	556	557							
3	558	559								
4	502	504	507	508	510	512	600	602	516	
5	454	452	456	468	472	450	458	465	471	473

C MODEL OUTPUT

COMPLETION TIMES, FASTEST TO SLOWEST, EVERY 10TH PERCENTILE
134.0161 152.3820 161.5413 166.9992 172.9557 177.7338 183.3907
188.7629 197.0742 203.3185 230.5410

CRITICAL MAN	1	0	2	0	3	0	4	0	5	200
IDLE TIME	1	75.6	2	90.4	3	91.0	4	66.1	5	18.0

Figure 2. Examples of task library entries, model input, and model output.

Figure 3 shows that reducing from ten to six the number of men assigned to set-up and boresight has only a small effect on completion time. This is because the improved efficiency of assigned crew members generally compensates for the lesser number of men. The six man unit is on the average only 5% slower than a ten man unit, but as unit size is further reduced to five the time penalty increases to 11.0%. Neither increase in completion time appears substantial given the corresponding increased availability of support personnel.

Data in Figure 3 also indicate that a reduction from eight to five men during firing adds a first-round firing time penalty of 8.6% per mission but provides five men to perform support duties. Further reducing the fighting unit to four would cause the time required to fire a single-round mission to increase by 12.7% over base rate.

The TM sequence for march-ordering a howitzer section involves nine men since the Gun Guide is usually elsewhere establishing a new location. Here again a reduction in crew members makes very little difference until a five man unit is used. Figure 4 shows that five man units accrue a 14.7% time penalty, but the penalty increases to 28.6% when only four men perform

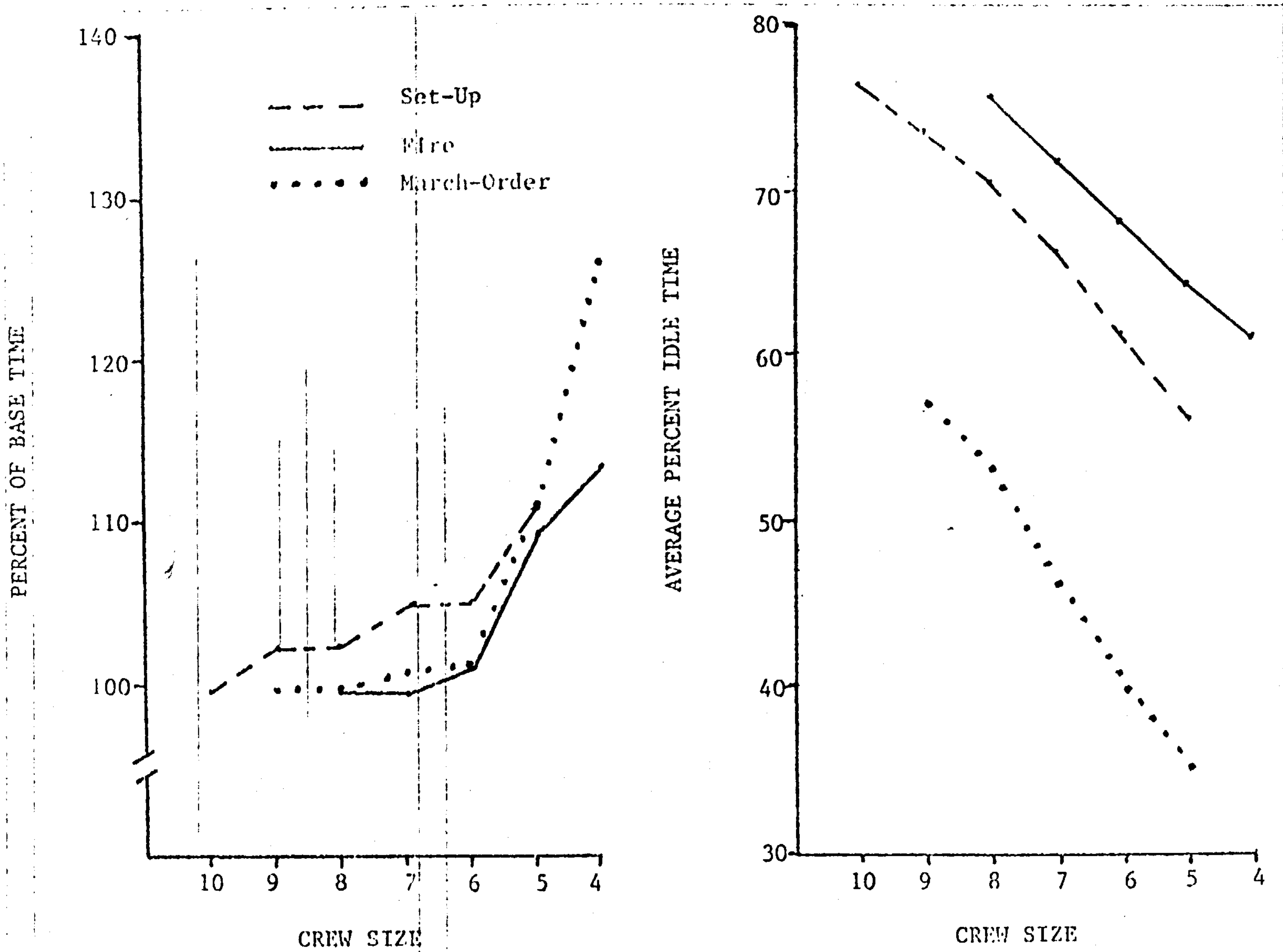

Figure 3. Times required to set-up, fire and march-order an M109A1 howitzer section and crew member idle times for various crew sizes.

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the march-order tasks. Thus, four men could be made available for support duties without significantly impairing performance on march-order tasks.

From this analysis of crew structure effects on set-up, firing, and march-order times, it appears that fighting tasks would not necessarily be impaired when operating with a reduced crew if the crewmen are more efficiently assigned their tasks. By doing this, not only is idle time reduced but personnel are freed to perform necessary support duties.

GOALS FOR WEAPONS CREW STRUCTURES

In considering the results of our simulation of howitzer crew operations, we have formulated five goals and have examined our data to determine which crew structure best meet these goals. The goals we think must be met by an adequate crew structure are:

1. Be able to emplace, fire, march-order and transfer the section in an acceptable time or at an acceptable rate.
2. Permit enough people to be assigned to the support functions that lack of support does not reduce the section's fighting ability to an inadequate level.
3. Have a reasonable capability to respond, in a degraded mode, when section personnel are lost.
4. Be effectively applied and practiced in a peacetime milieu.
5. Transfer to battle conditions with a minimal burden on the crew.

Data generated by the ARI Crew Performance Model imply that howitzer crews can be significantly modified to provide a better base for fighting a howitzer section. There are several ways in which the existing crew structure can be changed. One particularly attractive rearrangement is to divide the ten man crew into two virtually identical five man units (5/5), a split-crew approach, that alternates the units between the fighting and support tasks.

A 5/5 split-crew structure is proposed in Table 2 where it is compared to the crew as it is designated in the Technical Manual. The TM crew structure consists of ten positions, and one person is assigned to each position. The 5/5 crew structure provides two units, a "Red Unit" and a "Gold Unit", which are identical except that one unit contains the Section Chief and the other is supervised by a Unit Chief. During extended continuous operations, these units would alternate between the fighting tasks and the support tasks. A summary of the fighting task decrements and the time available for support tasks for such a division is shown in Table 3.

When a gun is emplaced according to the sequence defined in the TM, the entire ten man crew, including the Gun Guide, is involved. In the 5/5 solution, five firing unit members and the Gun Guide (6 men) are involved. The median set-up time is only 5% longer for the 5/5 crew than the standard

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Table 2

TM and Split-Crew Structures

TM STRUCTURE

Chief of Section	(CS)	Cannoneer #1	(#1)
Gunner	(G)	Cannoneer #2	(#2)
Assistant Gunner	(AG)	Cannoneer #3	(#3)
Howitzer Driver	(HD)	Cannoneer #4	(#4)
Section Driver	(SD)	Cannoneer #5	(#5)

SPLIT-CREW STRUCTURE

Red Unit		Gold Unit	
Chief of Section	(CS)	Unit Chief	(UC)
Gunner	(G)	Gunner	(G)
Cannoneer #1	(#1)	Cannoneer #1	(#1)
Howitzer Driver	(HD)	Howitzer Driver	(HD)
Section Driver	(SD)	Section Driver	(SD)

crew. This is a rather minor time penalty and, in a real sense, even this may not constitute a liability. Note that with the 5/5 structure, four crewmen are available during the emplacement process to perform support functions. In a hostile environment these four men would most logically be assigned to set up camouflage or emplace screens. Therefore, when the gun is reported up and ready in the 5/5 case, some of the support work would already have been completed; in the TM case the support work would all remain to be done. Thus, the actual time required to have the gun both up and ready and protected would probably be less in the 5/5 case.

The effect of shifting to a split-crew structure is somewhat greater for firing than for emplacement. We estimate the median time to prepare and fire a first round increases by 8.6% if the 5/5 structure is used. Again, however, this is compensated for by there being five rather than two men available to perform support functions.

A more subtle form of compensation during the firing cycle (or any other sequence) is that with only five men involved, there are no excess crew members. Consequently, there is a real pressure to improve crew effectiveness by removing problems rather than merely working around them by applying another pair of hands. Indeed, when the work flow during firing was examined we identified at least three materiel changes which, if implemented, would make the five man firing operation faster than the standard eight man operation. For example, because howitzer crews are not issued strap cutters and must improvise accordingly, cutting straps averages 41 seconds per eight-round pallet. Therefore, an average of about five seconds per round fired is the cost of the poor equipment furnished to cut straps. Clearly, if a strap cutter were placed in the tool kit on the section vehicle, the time required to open a new pallet would be reduced considerably--probably to under five seconds--with a consequent reduction of median one round firing time by about four seconds. When the model was used to evaluate the effect of a hypothetical situation in which this and other material changes were included, we found that the median completion time for the 5/5 structure during firing was actually faster than the present eight man approach.

Table 3

Times to Complete Fighting Task Sequences and Times Available for Support Duties for the TM and Split-Crew Structures

Activity	Men Available For Fighting Functions		Men Available For Support Functions		5/5 Time Penalty
	TM	5/5	TM	5/5	
Emplace	9 + GG	5 + GG	0	4	5.0%
Fire	8	5	2	5	8.6%
March-order	9 + GG	5	0	5	17.7%
In-transit	9 + GG*	9 + GG*	1	1	0.0%

*The Gun Guide is normally not in-transit with the crew.

The march-order sequences constructed for five man units also shows a time penalty, adding 14.7% to the nine man median completion time. However, this decrement is more illusory than real. The march-order base case follows the TM assumption that nine men are immediately available so that the march-order sequence begins with all nine men working. In an actual battle situation, however, a hasty departure would surely begin with some of those nine men assigned to perimeter defense or other support functions. Thus, nine men are not immediately available for work. The apparent 14.7% decrement would have been less if the TM sequence did not begin unrealistically with eight men at the gun and one nearby (the Gun Guide having already departed). Actually, given the number and diversity of the support tasks which must be performed, the 5/5 structure with an independent, self-contained support unit may well be faster.

The in-transit situation would be unaffected by the change to a 5/5 crew structure. In the 5/5 system, the unit assigned to the fighting tasks would provide two drivers, two air guards, and an NCO in-charge. The support unit would provide a gun guide who would probably be off with the advance party. The other four support unit members would do those minor personal support duties which are possible while being transported or else they would be idle. This is essentially the work/idle situation that presently exists while in-transit.

It seems that a 5/5 division provides no significant disadvantages in the emplacement and march-order sequences and that the decrement which accrues in the first-round-out situation can be overcome with minimal improvements in the equipment available to a howitzer crew. Thus, a 5/5 crew split meets the first goal--fighting the howitzer in an acceptable time--as well as the present TM crew structure.

The second goal--having enough men available to support the section--is clearly better met by the 5/5 split-crew structure. Indeed the 10, 8, and 9 men specified for the set-up, firing and march-order sequences in the TM structure leave at most only two men to perform support duties. The split-crew structure makes available five support personnel at all times.

The 5/5 structure is also well suited as a point of departure for degraded mode operations (Goal 3). Battery losses of up to one man per section can be absorbed by reducing the support task units from five to four men. If further battery losses occur, men could be pulled from fighting task units until sections are operating in a 4/4 condition. In that case, sections, and the battery to which they are attached, would be operating more slowly and at a greater risk of suffering either adverse actions or having inadequate replenishment capability. More likely, however, the battery with 20% casualties would have lost essential materiel. Personnel from inoperative sections would then be available to other sections as replacements to create five man firing units; fewer viable sections would, of course, be the result.

Differences between the TM assignment method and the 5/5 concept also favor the 5/5 concept when peacetime manning problems are considered (Goal 4). Two basic manning problems exist in the present Field Artillery cannon batteries: Many batteries do not have a full complement of personnel, and high levels of turbulence characterize most section crews. These two problems have far more significant consequences for the TM structure than they would have for the 5/5 structure. The most obvious problem associated with using the 10/8/9 set-up/fire/march-order structure is that a section must have ten crew members to use it. Realistically, this is seldom the case; hence, there is usually no opportunity to create or to practice ten man crews. A 5/5 split-crew structure, on the other hand, requires fewer personnel in order to form units for training or fighting. The TM structure is also particularly vulnerable to the effects of turbulence. The absence or shifting of personnel from a crew because of internally created turbulence or the replacement of existing crew members by new personnel creates situations that are hard to overcome since section activities are not currently standardized. As crews now exist there is little likelihood that a crewman serving in a particular position on a particular crew will perform the same tasks when serving the same position but on another crew. In contrast, with a 5/5 split-crew structure, task assignments would be standardized, thereby minimizing the need to retrain when personnel change positions or crews.

As for Goal 5, the 5/5 structure appears superior for moving from a peacetime to a wartime situation with minimal impact. Standardization, which can be readily accomplished with the 5/5 approach, makes it possible to bring a battery up to full strength by merely adding five man units. As new units arrive at a battery, Section Chiefs simply convert sections from half manned sections to fully manned sections. This saves Section Chiefs from the need to move from a poorly defined crew structure to the ten man TM structure, a structure which as we have suggested is not very efficient.

PERFORMANCE DURING CONTINUOUS OPERATIONS

Our discussion until now has shown how the ARI Crew Performance Model can estimate crew size/structure effects under first-day or near optimal conditions. In a more realistic scenario, however, howitzer crews will likely be fighting for extended periods—up to 8 days—under high work/low rest battle conditions. Anecdotal and experimental evidence on the effects of these conditions on performance suggests that the effects will be both negative and substantial and will increase as the duration of combat and sleep loss increases. For that reason the model has been equipped to adjust first-day task performance as some function of accrued impairment from Day 1 through Day N. Also, because different types of tasks will be differentially affected by sleep loss, the model is equipped to apply decrements according to task type.

In order to determine what data are available for estimating long-term performance under the conditions noted above, we have conducted an extensive literature search and review of the effects on performance of total and partial sleep loss and work/rest cycles. Only research on behavioral effects, vis-a-vis subjective and physiological measures, were considered. Both the open literature and government sources were searched. The results of this review will be reported elsewhere in detail. We also examined various task taxonomies to determine how the howitzer tasks and tasks in the literature might best be classified. In the end, none was suitable, primarily because of the nature of the measures used in the literature, so we prepared a rather global classification scheme for our use.

The literature describing performance after varying periods of total sleep loss provided over 205 titles, with approximately two-thirds of these studies testing performance after less than 72 hours of total sleep loss. Approximately 40 of these articles documented information useful for determining decrement values for use in our model. Considerably less research was found on the effects of partial sleep loss and on performance under relevent work/rest ratios. In fact, only 55 titles in these areas were found and fewer than ten have documented evidence suitable for use in constructing decrement tables for our model.

Table 4

Documented Studies of the Behavioral Effects of Total and Partial Sleep Deprivation as a Function of Task Type and Time

TEST DAYS	1	2	3	4	5	6	7	8
Physical Strength	T	T	T	T				
Gross Body Movement and General Coordination	T	T	T	T				
Fine Movement and Eye-Hand Coordination	T	T	T	T	T P	P	P	P
Following Directions and Short-Term Memory	T P	T P	T P	T P	P	P	P	P
Rules, Regulations and Long-Term Memory	T	T						
Problem Sensitivity and Responsiveness to Change	T P	T P	T P	T P	T P	T P	P	P
Decision Making and Taking Action	T		T					
Mental Effort, Attention and Concentration	T P	T P	T P	T P	T P	P	P	P

T = Total sleep loss. P = Partial sleep loss or work/rest ratio.

Table 4 is a general overview of our survey with the data available from the literature presented as a function of task type and duration of test period. Separate entries are shown for total sleep deprivation and work/rest ratio studies. Very little work has been done in these areas and most of what has been reported deals with periods of only a few days. Of the studies testing performance under realistic conditions, only one tested performance after an initial period of total sleep deprivation followed by periods when four hours of sleep per day--the maximum likely--were allowed. Some task types are notable for their lack of research documentation. Furthermore, within task types, a failure to standardize tasks and procedures contributes to considerable difficulty in interpreting results. Indeed, most of the studies represented in Table 4 suffer from one or more methodological problems of varying degrees of severity. Quite common, for instance, is failure to control for learning or circadian rhythm effects.

Thus, an extensive review of the literature on the effects of extended performance with reduced sleep illustrates the dearth of useful information available. For this reason, only a portion of the decrement table for use with the model can be completed based on data in the available literature, and even that portion, because of problems in the original research, is of limited value.

CONCLUSION

The ARI Crew Performance Model can be used as an analytic tool for evaluating the effects of crew structure on performance. Whether used with developing systems or systems in the field, the model can be of value in determining the effects of changes in crew size and the assignment of tasks on the relative efficiency of varying crew structures. However, before the model can be fully utilized, particularly when crew performance in a realistic battlefield scenario is being considered, a great deal of work remains to be done to determine the effects on human performance of extended, continuous performance under conditions of high work/low rest periods.

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