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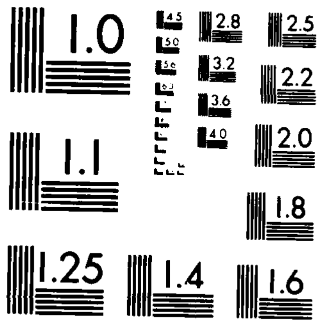

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MEMORANDUM REPORT BRL-MR-3426

COMPARISON OF THE OUTPUTS OF THE NORDEN BATTERY C^3 MODEL AND THE BALLISTIC RESEARCH LABORATORY MESSAGE PROCESSING MODEL

Alan R. Downs

January 1985

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US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report critiques the Norden Battery C^3 model and its ability to perform communication analyses in support of the Division Support Weapon System (DSWS) - later renamed the Howitzer Improvement Program (HIP). The Ballistic Research Laboratory Message Processing Model (BRLMPM) was used to perform the evaluation. Mathematical and statistical analyses of mean mission durations were performed as part of the study. It was found that if certain modifications are made to the Norden model and its data inputs, it should be adequate to perform the needed analyses.

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I. INTRODUCTION

The United States Army is currently investigating the need for a new howitzer to replace the M109A2/A3. The alternatives being considered are: continuing with the existing system, product improving the M109A2/A3, developing a completely new howitzer, or procuring the best available foreign made howitzer. These investigations, which are being guided by the office of the Project Manager for Cannon Artillery Weapon Systems (PM/CAWS), were referred to as the Division Support Weapon System (DSWS) study. The study was subsequently named the HIP study (for Howitzer Improvement Program) but the DSWS designation will be used in this report. Issues receiving the heaviest attention are those that have a growth potential because of new technologies, i.e., increased rate of fire, improved fire control, better ammunition resupply and handling, and improved command, control, and communications (C^3).

The methodology used to address C^3 issues for DSWS has been the Norden Battery C^3 model. Since this model is unvalidated, PM/CAWS asked the US Army Ballistic Research Laboratory (BRL) to use its Ballistic Research Laboratory Message Processing Model (BRLMPM) to analyze the results obtained with the Norden model. Such an analysis can not be considered to be a validation since the BRLMPM itself is unvalidated. However, a comparison should provide much information about the manner in which both models work, the assumptions upon which each is based, and the results one could expect from using either of the models.

This report discusses the comparison of the two models. The report is organized in the following way. Section II contains a description of the background to the study. Section III contains operational descriptions of the Norden Battery C^3 model and the BRLMPM. Section IV describes the way the study was conducted. Section V contains the results and analysis obtained by a direct comparison of the two models. Section VI contains an analysis of the effects of queuing in the BRLMPM. Section VII contains a set of conclusions about the workings of both models and some recommendations for modifying both models.

II. BACKGROUND

During the 1970s, the United States Army concluded that its fire support capability was inferior to that of potential adversaries due to their three-to-one numerical advantage in fire support assets. The qualitative superiority that had long existed was also eroding due to extensive force modernization being undertaken by the Soviet Union and other countries. To counter the increased threat, the United States Army guided into the development cycle a number of new systems whose purpose was to improve the U.S. Army's fire support capability. These systems included the TPQ-36/37 mortar and battery locating radars (FIREFINDER), moving target indication (MTI) radars, and remotely piloted vehicles (RPVs) to improve target acquisition capability; dual purpose improved conventional munitions (DP-ICMs), the multiple launcher rocket system (MLRS), and Copperhead to increase target engagement performance; and the fire support team digital message device (FIST DMD), the position and azimuth determining system (PADS) and the tactical fire direction system (TACFIRE) to improve field artillery system responsiveness. To improve system responsiveness and to reduce system vulnerability, the Advanced Field Artillery Tactical Data System (AFATDS) has entered the development cycle. Changes in field artillery operations are also being considered. Emphasis has shifted away from the traditional "lazy W" battery formation and toward a looser battery formation in order to take advantage of treelines or other natural camouflage. Spread battery and even autonomous howitzer operation to compound the enemy's counterfire problems are being addressed through changes in fire control, position determination, and muzzle velocity determination instrumentation.

Much of the impetus for the rapid changes in equipment and tactics was provided by the Battleking study.[1] In September 1974 the Assistant Secretary of the Army (Research and Development) requested the Chief of Research, Development and Acquisition to conduct a study of the total artillery

[1] *Office, Deputy Chief of Staff for Research, Development, and Aquisition, "Report of Artillery System Study Group (Task Force Battleking)," December 1974.*

system. The results of the study (not discussed here) have shaped much of the artillery system thinking that has subsequently evolved and influenced the development cycle of many of the previously listed items.

During the 1970s and continuing into the 1980s, a series of tests were sponsored by the US Army Human Engineering Laboratory (HEL) to assess field artillery performance using traditional and developmental equipment and doctrine.[2] These tests are the Human Engineering Laboratory Battalion Artillery Tests (HELBAT) and have been conducted at one to three year intervals at Ft. Hood, Texas and Ft. Sill, Oklahoma. The HELBAT exercises have uncovered numerous "soft spots" in field artillery performance and in many cases have recommended procedural and/or equipment changes needed to rectify field artillery weaknesses. For example, pertinent to the study described in this report, a conclusion resulting from HELBAT 7 (Feb 1979) was that the field artillery command, control, and communications (C^3) problem was more severe than had been previously believed. For this reason, C^3 was made the first priority item for HELBAT 8 (Oct 1981).

Another effort undertaken to investigate field artillery C^3 performance is the Artillery Control Environment (ACE). This program, initiated by the US Army Ballistic Research Laboratory (BRL), entails the development of a fire support control simulator which is expected to serve as a methodology for developing and evaluating various alternatives in the technological, materiel, organization, and operational aspects of fire control. ACE is an interactive, real-time, multi-player fire support control simulator with which problems can be identified and analyzed, and potential solutions to these problems evaluated using a variety of systems and scenarios. With ACE, various hardware, software, human interface technology, and systems concepts can be studied without expending the financial, time, and manpower resources needed to build complete dedicated hardware. Plans are currently being made to use ACE to investigate some general problem areas including artillery system training, decision and control theory applications, man-machine interface requirements, and the application of artificial intelligence, gaming theory, and distributed decision-making processes to fire support control automation.[3]

The Ballistic Research Laboratory Processing Model (BRLMPM) was initially developed as part of the ACE Program but, since it is actually a model rather than a technology, has become a stand-alone entity. The BRLMPM was developed as a tool for tracing the flow of messages through any communications network. The version used in the study described in this report is based on TACFIRE.

For the past five years or so, the US Army has been looking intensively at the possibility of developing a new howitzer to replace the 155mm M109A2/A3 which is currently being used by the field artillery in a direct support role. This effort first centered around the enhanced self-propelled artillery weapon system (ESPAWS) study. The purpose of that study was to examine new technologies and materiels with the objective of making them available during the design process of a new howitzer. In analyzing the threat the new howitzer would be expected to counter the various roles played by the field artillery, and the manner in which it could play those roles with existing and proposed equipment were studied in detail. The ESPAWS effort was directed by the Large Caliber Weapon System Laboratory (LCWSL) of AMCCOM and consisted of both US Army laboratory in-house efforts and commercial contracts.

During 1981 the ESPAWS effort was phased into the Division Support Weapon System (DSWS) study which was concerned with incorporating the new technologies into system design. To provide more effective management of the DSWS program and to assure that valid methodology would underlie pertinent decision making, a System Analysis Working Group (SAWG) was established by PM/CAWS.

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[2] *R.B. Pengelley, "HELBAT - The Way to Tomorrow's Artillery?," International Defense Review, 1/1980.*

[3] *Barry L. Reichard, "Fire Support Control at the Fighting Level," BRL Special Publication No. ARBRL-SP-00021, July 1981. (ADB 059550L)*

This working group provides a forum for the exchange of ideas, methodology, and data among those responsible for the DSWS system analysis. One of its areas of emphasis is in C^3 analysis since field artillery communications is a major obstacle to the timely completion of field artillery missions. The relative newness of the field artillery C^3 concern has meant that the methodology used to address this issue is also new and, since it is often based on limited field data, is inadequately validated.

The objectives of the study described in this report can be considered to be answers to a set of specific questions. What are the assumptions that drive the Norden model? Are these assumptions compatible with standard field artillery tactics? How does the Norden model work? How do the results obtained with the Norden model compare with those obtained with the BRLMPM? How do these results compare with whatever results are available from field trials? One additional objective was added to satisfy BRL needs. What weaknesses in the BRLMPM have been found by performing the comparison?

III. METHODOLOGY AND MODEL INPUTS

The Norden Battery C^3 model and the BRLMPM are described in references four through six. Both models were designed to simulate the field artillery communications system in its ability to manage, transmit, and process the messages needed to conduct assigned fire missions. The two models are quite similar in many of their aspects but differ in several important ways. In the discussion that follows, the two models will be described as if they were a single model. Only where pertinent differences between them exist will the contrasting characteristics of the two models be cited.

Both models are characterized by a set of missions, each of which is a time-ordered sequence of messages needed to perform a fire mission, a network over which the messages and acknowledgements must flow, and a set of rules to describe the manner in which the individual messages are processed.

The field artillery network simulated in both models is shown in Figure 1. Five unit (nodal) types were included in the simulation. Each unit is represented in the figure as a geometrical shape (triangle, circle, or square) and is located on a horizontal line with the type of unit indicated on the right side of the figure. The line connecting any two units is a communication link. One or more links that are assigned the same radio frequency comprise a net. The simulations performed for this study divided the network of Figure 1 into six nets. Three of these nets are fire direction (FD) nets and comprise those links above the level of battery and contained within one-third of the figure. The gun orders (GO - unofficial usage) nets are those links that connect each battery to its assigned gun sections. In the Norden model there is a link to each individual howitzer, not just to the gun sections. It can be seen that each FD net is comprised of twelve links and each GO net is comprised of two links.

A list of some message processing rules applicable to the BRLMPM follows.

- The field artillery network is subdivided into a number of individual nets.
- Only one message at a time can be transmitted over any net.
- When each message reaches its destination, a processing delay time must pass before the next message can be generated.
- Queues may develop at any processing point (node). The messages in any queue are

[4] *Allan D. Aronoff, et al, "Enhanced M109A2/A3 Concept Definition Study, Phase 1B, Final Scientific and Technical Report," Norden Systems, Inc., 31 July 1982.*

[5] *Morton a Hirschberg, "The BRL Message Processing Model (BRLMPM)," BRL Report No. ARBRL-TR-02464, January 1983. (ADA 125450)*

[6] *Alan R. Downs and Morton A. Hirschberg, "A Sensitivity Analysis of the BRL Message Processing Model (BRLMPM) Data Inputs," BRL Memorandum Report No. ARBRL-MR-03230, December 1982. (ADA 123335)*

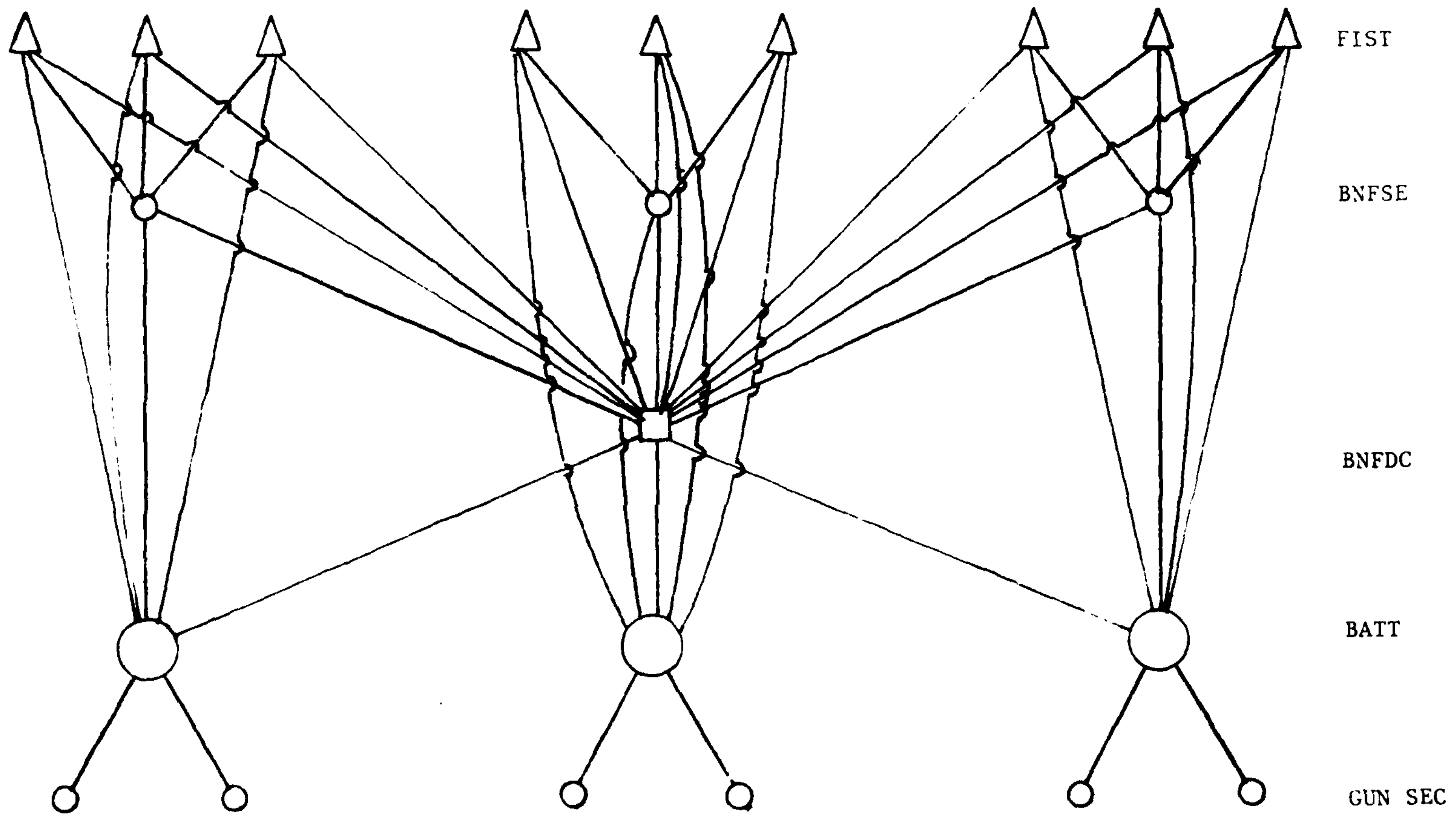

Figure 1. The Field Artillery Communications Network Simulated in Both Models

processed in the order in which they entered the queue.

- When a message is received at any node, it must be acknowledged before the next message can be sent.

The Norden model has a similar set of rules. It will be seen that even a slight difference in the rules can make a substantial difference in model performance.

The fire missions in both models are represented by a set of sequential messages between units and the processing delays at each unit. In the original Norden study, nine different types of fire missions were considered. In the study described here only four of these were considered, namely, FIST originated missions in which the firing battery is under centralized battalion control (non-autonomous operation). The four fire missions considered in this study are shown in Tables 1 through 4 and are equivalent to Figures B-1, B-2, B-3, and B-5 of reference 4. Certain pieces of needed information (delays or message lengths) were missing in the referenced report and were therefore obtained from other sources. These inserted pieces of information are indicated by asterisks.

These mission profiles were input directly in the Norden model but had to be modified prior to use in the BRLMPM. The reasons for and the nature of these modifications will be discussed in the next section. The processing delays shown in Tables 1 through 4 represent mean times. The values used in running the models were obtained by sampling from the distributions of these mean delay times. In the Norden model the distribution is exponential; in the BRLMPM the distribution is triangular.

The simulations performed with the two models were based on combat scenarios in which the four mission types were represented in different proportions. Six such scenarios were considered and the mission mixes for each are described in Table 4-3 of reference 1. The information in this table that is pertinent to the BRLMPM was converted to frequencies of occurrence for each of the four mission types. The frequencies for each mix are presented in Table 5.

The messages that characterize each of the four mission profiles are represented by their lengths in bits. In the BRLMPM the actual length used is again obtained by sampling from a triangular distribution; however for this study, the sampling range was made very narrow (only two bits) to more accurately duplicate the workings of the Norden model.

IV. PROCEDURE

The Norden study was conducted using twelve mission mixes. Only six of these, the non-autonomous missions, were duplicated with the BRLMPM. Channel capacity (or transmission rate) and nodal service (delay) time were both used as independent variables in the Norden model, thus generating two data sets for each mission mix. In the BRLMPM runs, only channel capacity, with transmission rates of 300, 1200, and 4800 bits/sec, was used as an independent variable. The six measures of effectiveness used in the Norden study are:

- fraction of missions completed,
- mean mission duration,
- FD net queue entries,
- FD net fractional utilization,
- GO net queue entries, and

TABLE 1. AREA MISSION-AT MY COMMAND, BN. CONTROL

MESSAGE NUMBER	SENDER	ADDRESSEE	MESSAGE TYPE	DELAY (SEC)	LENGTH (BITS)	COMMENTS
1	FIST	BNFDC	FRGRID	53.0	528	
2	BNFDC	BNFSO	FM:RFAF	5.0	6048	
3	BNFDC	BATT	FM:FC	2.0	6048	
4	BNFDC	FIST	FM:MTO	1.0	3108	
5	BATT	GUNS	GO	2.5	3840	1ST ADJUST
6	GUNS	BATT	ACK	2.5	390	1ST ADJUST
7	BATT	GUNS	POLL	15.0	3120	1ST ADJUST
8	GUNS	BATT	READY	1.0	390	1ST ADJUST
9	BATT	FIST	READY	2.5	1260	1ST ADJUST
10	FIST	BATT	FIRE	0.0*	528	1ST ADJUST
11	BATT	GUNS	FIRE	2.5	280	1ST ADJUST
12	BATT	GUNS	POLL	1.1	3120	1ST ADJUST
13	GUNS	BATT	SHOT	2.5	390	1ST ADJUST
14	BATT	FIST	SHOT	2.5	1260	1ST ADJUST
15	BATT	GUNS	POLL	1.1	3120	1ST ADJUST
16	GUNS	BATT	COMPLETE	2.5	390	1ST ADJUST
17	BATT	FIST	SPLASH	52.5	1260	1ST ADJUST
18	FIST	BNFDC	SUBS ADJ	3.0	528	2ND ADJUST
19	BNFDC	BATT	FM:FC	2.0	6048	2ND ADJUST
20	BATT	GUNS	GO	2.5	3840	2ND ADJUST
21	GUNS	BATT	ACK	2.5	390	2ND ADJUST
22	BATT	GUNS	POLL	15.0	3120	2ND ADJUST
23	GUNS	BATT	READY	1.0*	390	2ND ADJUST
24	BATT	FIST	READY	2.5	1260	2ND ADJUST
25	FIST	BATT	FIRE	0.0*	528	2ND ADJUST
26	BATT	GUNS	FIRE	2.5	280	2ND ADJUST
27	BATT	GUNS	POLL	1.1	3120	2ND ADJUST
28	GUNS	BATT	SHOT	2.5	390	2ND ADJUST
29	BATT	FIST	SHOT	2.5	1260	2ND ADJUST
30	BATT	GUNS	POLL	1.1	3120	2ND ADJUST
31	GUNS	BATT	COMPLETE	2.5	390	2ND ADJUST
32	BATT	FIST	SPLASH	52.5	1260	2ND ADJUST
33	FIST	BNFDC	FFE	3.0	528	FIRE FOR EFFECT
34	BNFDC	BATT	FM:FC	2.0	6048	FIRE FOR EFFECT
35	BATT	GUNS	GO	2.5	3840	FIRE FOR EFFECT
36	GUNS	BATT	ACK	2.5	390	FIRE FOR EFFECT
37	BATT	GUNS	POLL	15.0	3120	FIRE FOR EFFECT
38	GUNS	BATT	READY	1.0	390	FIRE FOR EFFECT
39	BATT	FIST	READY	2.5	1260	FIRE FOR EFFECT
40	FIST	BATT	FIRE	0.0*	528	FIRE FOR EFFECT
41	BATT	GUNS	FIRE	2.5	280	FIRE FOR EFFECT
42	BATT	GUNS	POLL	1.1	3120	FIRE FOR EFFECT
43	GUNS	BATT	SHOT	2.5	390	FIRE FOR EFFECT
44	BATT	FIST	SHOT	2.5	1260	FIRE FOR EFFECT
45	BATT	GUNS	POLL	1.1	3120	FIRE FOR EFFECT
46	GUNS	BATT	COMPLETE	2.5	390	FIRE FOR EFFECT
47	BATT	FIST	SPLASH	47.5	1260	FIRE FOR EFFECT
48	FIST	BNFDC	FOM&SURV	3.0	528	
49	BNFDC	BNFSO	AFU:MFR	5.0	6048*	
50	BNFDC	BATT	EOM	2.0	2076	
51	BATT	GUNS	EOM	2.5	280	
52	GUNS	BATT	ACK	2.5	390	

*VALUE NOT GIVEN, OBTAINED FROM OTHER SOURCES.

TABLE 2. AREA MISSION-WHEN READY, BN. CONTROL

MESSAGE NUMBER	SENDER	ADDRESSEE	MESSAGE TYPE	DELAY (SEC)	LENGTH (BITS)	COMMENTS
1	FIST	BNFDC	FRSHIFT	48.0	528	
2	BNFDC	BNFSO	MOI	5.0	6048	
3	BNFDC	BATT	FM:RFAF	2.0	6048	
4	BNFDC	FIST	MTO	1.0	3108	
5	BATT	GUNS	GO	2.5	3840	1ST ADJUST
6	GUNS	BATT	ACK	2.5	390	1ST ADJUST
7	BATT	GUNS	POLL	15.0	3120	1ST ADJUST
8	GUNS	BATT	SHOT	2.5	390	1ST ADJUST
9	BATT	FIST	SHOT	2.5	1260	1ST ADJUST
10	BATT	GUNS	POLL	1.1	3120	1ST ADJUST
11	GUNS	BATT	COMPLETE	2.5	390	1ST ADJUST
12	BATT	FIST	SPLASH	22.5	1260	1ST ADJUST
13	FIST	BNFDC	SUBS ADJ	3.0	528	2ND ADJUST
14	BNFDC	BATT	FM:FC	2.0	6048	2ND ADJUST
15	BATT	GUNS	GO	2.5	3840	2ND ADJUST
16	GUNS	BATT	ACK	2.5	390	2ND ADJUST
17	BATT	GUNS	POLL	15.0	3120	2ND ADJUST
18	GUNS	BATT	SHOT	2.5	390	2ND ADJUST
19	BATT	FIST	SHOT	2.5	1260	2ND ADJUST
20	BATT	GUNS	POLL	1.1	3120	2ND ADJUST
21	GUNS	BATT	COMPLETE	2.5	390	2ND ADJUST
22	BATT	FIST	SPLASH	52.5	1260	2ND ADJUST
23	FIST	BNFDC	FFE	3.0	528	FIRE FOR EFFECT
24	BNFDC	BATT	FM:FC	2.0	6048	FIRE FOR EFFECT
25	BATT	GUNS	GO	2.5	3840	FIRE FOR EFFECT
26	GUNS	BATT	ACK	2.5	390	FIRE FOR EFFECT
27	BATT	GUNS	POLL	15.0	3120	FIRE FOR EFFECT
28	GUNS	BATT	SHOT	2.5	390	FIRE FOR EFFECT
29	BATT	FIST	SHOT	2.5	1260	FIRE FOR EFFECT
30	BATT	GUNS	POLL	1.1	3120	FIRE FOR EFFECT
31	GUNS	BATT	COMPLETE	2.5	390	FIRE FOR EFFECT
32	BATT	FIST	SPLASH	47.5	1260	FIRE FOR EFFECT
33	FIST	BNFDC	EOM&SURV	3.0	528	
34	BNFDC	BNFSO	AFU:MFR	5.0	6048*	
35	BNFDC	BATT	EOM	2.0	2076	
36	BATT	GUNS	EOM	2.5	280	
37	GUNS	BATT	ACK	2.5	390	

*VALUE NOT GIVEN, OBTAINED FROM OTHER SOURCES.

TABLE 3. COPPERHEAD MISSION-BN. CONTROL

MESSAGE NUMBER	SENDER	ADDRESSEE	MESSAGE TYPE	DELAY (SEC)	LENGTH (BITS)	COMMENTS
1	FIST	BNFDC	FRGRID	53.0	528	
2	BNFDC	BNFSO	FM:RFAF	5.0	6048	
3	BNFDC	BATT	FM:FC	2.0	6048	
4	BNFDC	FIST	MTO	2.0	3108	
5	BATT	GUNS	GO	2.5	3840	
6	GUNS	BATT	ACK	2.5	390	
7	BATT	GUNS	POLL	50.0	3120	
8	GUNS	BATT	READY	2.5	390	
9	BATT	FIST	READY	1.0	1260	
10	FIST	BATT	FIRE	0.0*	528	
11	BATT	GUNS	FIRE	2.5	280	
12	BATT	GUNS	POLL	1.1	3120	
13	GUNS	BATT	SHOT	2.5	390	
14	BATT	FIST	SHOT	2.5	1260	
15	BATT	GUNS	POLL	1.1	3120	
16	GUNS	BATT	COMPLETE	2.5	390	
17	BATT	GUNS	POLL	21.1	3120	
18	BATT	FIST	SPLASH	27.5	1260	
19	GUNS	BATT	SHOT	2.5	390*	
20	BATT	FIST	SHOT	2.5	1260	
21	BATT	GUNS	POLL	1.1	3120	
22	GUNS	BATT	COMPLETE	2.5	390	
23	BATT	FIST	SPLASH	52.5	1260	
24	FIST	BNFDC	EOM:SURV	3.0	528	
25	BNFDC	BNFSO	AFU:MFR	5.0	6048*	
26	BNFDC	BATT	EOM	2.0	2076	
27	BATT	GUNS	EOM	2.5*	280	
28	GUNS	BATT	ACK	2.5	390	

*VALUE NOT GIVEN. OBTAINED FROM OTHER SOURCES.

TABLE 4. FIRE FOR EFFECT-FIST ORIGINATED, BN. CONTROL

MESSAGE NUMBER	SENDER	ADDRESSEE	MESSAGE TYPE	DELAY (SEC)	LENGTH (BITS)	COMMENTS
1	FIST	BNFDC	FFE	43.0	528	
2	BNFDC	BNFSO	FM;RFAF	5.0	6048	
3	BNFDC	BATT	FM;FC	2.0	6048	
4	BNFDC	FIST	MTO	1.0	3108	
5	BATT	GUNS	GO	2.5	3840	
6	GUNS	BATT	ACK	2.5*	390	
7	BATT	GUNS	POLL	15.0	3120	
8	GUNS	BATT	SHOT	2.5	390	
9	BATT	FIST	SHOT	2.5	1260	
10	BATT	GUNS	POLL	1.1	3120	
11	GUNS	BATT	COMPLETE	2.5	390	
12	BATT	FIST	SPLASH	47.5	1260	
13	FIST	BNFDC	EOM&SURV	3.0	528	
14	BNFDC	BNFSO	AFU;MFR	5.0	6048*	
15	BNFDC	BATT	EOM	2.0	2076	
16	BATT	GUNS	EOM	3.6	280	
17	GUNS	BATT	ACK	2.5	390	

*VALUE NOT GIVEN. OBTAINED FROM OTHER SOURCES.

TABLE 5. FREQUENCY OF OCCURRENCE OF MISSION TYPES

MIX	FREQUENCY OF OCCURRENCE OF MISSION NUMBER 1	2	3	4
1	0.66	0.00	0.23	0.11
2	0.00	0.66	0.23	0.11
3	0.00	0.00	0.23	0.77
4	0.10	0.10	0.23	0.57
5	0.22	0.22	0.23	0.33
6	0.33	0.28	0.23	0.16

- GO net fractional utilization.

The same measures of effectiveness were addressed using the BRLMPM. For this study, the six mission mixes and the three transmission rates examined resulted in 18 different combinations. Since six different responses were measured for each mix - rate combination a total of 108 data points were generated. None of the combinations was replicated.

The mission initiation information used in the Norden simulation was provided to the BRL by Norden personnel. This information is shown in Table 6. A total of 321 missions were initiated in the Norden study, the first occurring at 245 minutes (an arbitrary zero time); the final one at 598 minutes. Since the Norden model has one feature that the BRLMPM does not, namely, the ability to delete missions in progress when a target perishability limit is exceeded, these data were edited prior to use in the BRLMPM. The criterion used was that if a given target duration was less than ten minutes, no mission was initiated in the BRLMPM to engage the target. (This procedure is artificial in that it presupposes information not available to the FIST at the time of target acquisition.) The net effect of this expedient is to eliminate some messages included in the Norden simulation (those assigned to perishable targets) and to include some messages not included in the Norden simulation (those completing other missions the Norden simulation would have terminated due to target perishability), with the hope that the effects tend to balance out. In the BRLMPM simulation, 95 of the 321 targets were discarded prior to firing; thus 226 missions in 5.88 hours (598 minutes - 245 minutes) were initiated.

Both models were driven by the mission initiation sequence shown in Table 6. All the missions shown in this table were initiated in the Norden simulations. In the BRLMPM simulation the missions for which the target duration was less than ten minutes were not initiated. These missions are indicated by asterisks.

The mission initiation sequence used in the BRLMPM simulation is shown in Figure 2. The solid curve is a smooth fit to those points in Table 6 not indicated by asterisks. The dashed lines represent instantaneous mission initiation rates and can be compared to the slope of the solid curve. As can be seen, the mission initiation rate at the start of the simulation is about 200 missions/hour and steadily decreases to about 20 missions per hour at the end of the simulation 5.88 hours later.

V. RESULTS

A. A Priori Predictions of Model Performance

The time required to complete a single mission can be estimated for each model by adding the time needed to transmit all messages required to complete the mission, the nodal delays resulting from message processing, and some non-productive delays resulting from the nature of the field artillery procedure or communications system.

It is a simple matter to calculate the expected mission duration for the Norden model. The mission duration is simply the number of bits required to perform the mission divided by the channel capacity (or transmission rate) in bits/second, plus the total nodal delay time. Three channel capacities were considered in this study: 300, 1200 and 4800 bits/second. The results of this calculation for the four mission profiles of Table 1-4 are shown in Table 7.

The situation is not as simple for the BRLMPM for several reasons. First, a perusal of Tables 1 to 4 shows that the only messages that are acknowledged are gun orders. This procedure is in line with Marine Corps procedure with the Marine Integrated Fire and Air Support System (MIFASS) on which the Norden Battery C^3 model is based. It is not, however, in line with Army procedure in which all

TABLE 6. MISSION INITIATION TIMES USED IN BOTH MODELS.

NO.	INIT. TIME (MIN)	DURA-TION (MIN)	NO.	INIT. TIME (MIN)	DURA-TION (MIN)
1	245	21	41	270	56
2	245	21	42	270	56
3	245	27	43	270	56
4	248	20	44	270	56
5	248	21	*45	271	6
6	248	54	46	272	29
7	248	42	47	272	50
8	250	45	48	272	50
9	250	42	49	272	29
10	250	42	50	274	28
11	255	21	*51	275	7
12	255	17	52	276	24
13	255	12	53	276	43
14	255	11	54	276	24
15	255	21	55	276	43
16	255	17	56	276	43
*17	259	4	57	276	24
18	259	29	58	276	24
19	260	20	59	276	43
*20	260	4	60	276	43
21	260	11	61	276	43
*22	261	3	62	276	43
23	262	15	63	279	17
24	262	15	64	279	17
*25	263	0	65	279	17
*26	265	6	66	279	33
*27	265	1	67	279	33
28	265	12	68	280	18
29	267	18	69	280	18
30	268	20	70	280	18
31	268	20	71	280	41
32	269	21	*72	282	7
33	269	21	73	282	26
34	269	21	74	282	26
35	269	21	*75	284	6
36	270	23	*76	286	0
37	270	56	*77	286	1
38	270	56	78	288	22
39	270	28	79	288	22
40	270	56	80	288	22

TABLE 6. (CONTINUED)

NO.	INIT. TIME (MIN)	DURATION (MIN)	NO.	INIT. TIME (MIN)	DURATION (MIN)
81	288	22	121	314	62
*82	289	0	122	314	62
83	290	26	123	314	62
*84	293	0	124	314	62
*85	293	0	125	314	62
*86	293	0	*126	316	0
*87	295	3	*127	316	6
88	295	21	*128	317	0
*89	296	1	129	320	16
*90	298	0	130	320	31
*91	299	5	*131	322	3
*92	301	3	132	324	32
*93	302	0	*133	326	1
*94	303	8	*134	327	0
*95	304	0	*135	327	0
*96	304	0	*136	329	0
97	304	60	137	329	22
98	304	60	138	329	22
*99	305	1	139	329	22
100	305	18	*140	330	4
*101	307	4	141	330	30
102	308	41	142	330	30
103	308	41	143	330	30
104	308	41	144	330	30
105	308	41	145	330	30
106	311	45	*146	332	0
107	311	22	147	332	19
108	311	22	*148	333	0
109	311	45	149	335	15
110	311	45	*150	336	0
111	311	22	151	336	117
112	311	45	152	336	117
113	311	45	153	336	117
114	311	45	154	336	117
115	311	45	*155	337	2
116	312	10	*156	337	0
117	312	10	*157	340	8
118	314	62	158	342	15
119	314	62	159	342	15
120	314	62	*160	345	0

TABLE 6. (CONTINUED)

NO.	INIT. TIME (MIN)	DURATION (MIN)	NO.	INIT. TIME (MIN)	DURATION (MIN)
*161	346	0	*201	405	0
162	352	48	202	405	40
163	352	48	203	405	40
*164	361	1	204	407	34
*165	365	0	*205	408	0
166	365	24	206	410	16
167	366	16	*207	413	9
*168	366	6	208	415	22
169	366	16	209	415	60
170	366	16	*210	419	1
171	366	16	211	425	30
*172	367	0	212	425	28
173	368	16	213	425	10
174	374	18	214	426	47
175	374	16	215	430	29
176	374	18	216	432	75
177	374	16	217	432	75
178	374	16	218	432	75
*179	376	0	219	432	75
180	378	45	220	432	75
181	378	45	221	432	75
182	380	31	222	432	75
183	380	31	223	432	75
*184	382	0	224	432	75
185	382	24	*225	434	0
*186	385	0	*226	439	0
*187	386	0	227	440	19
188	386	43	*228	442	5
189	386	43	*229	443	0
190	386	43	*230	449	3
191	386	43	*231	451	0
*192	389	0	*232	451	3
*193	393	9	233	454	35
*194	396	0	234	454	35
195	396	106	235	454	35
196	396	106	236	454	35
197	396	106	237	454	35
198	396	106	238	455	13
*199	397	5	*239	455	0
*200	399	0	*240	457	8

TABLE 6. (CONTINUED)

NO.	INIT. TIME (MIN)	DURATION (MIN)	NO.	INIT. TIME (MIN)	DURATION (MIN)
241	458	12	*281	521	0
242	459	23	*282	522	0
*243	461	0	283	525	16
244	462	12	284	525	16
*245	462	0	*285	526	0
246	474	28	*286	528	3
247	474	28	*287	531	3
248	479	36	*288	534	0
*249	480	3	*289	546	3
*250	484	0	*290	552	0
*251	490	5	291	554	17
*252	490	0	*292	555	0
253	494	18	293	556	18
254	494	18	294	556	18
255	494	18	295	556	18
256	495	22	296	564	40
257	495	22	297	565	21
258	495	22	298	565	21
259	495	22	299	565	21
*260	498	0	300	565	21
*261	499	2	301	566	27
262	501	66	302	566	27
*263	502	0	303	584	18
264	504	21	*304	585	7
265	504	21	*305	585	7
266	504	21	*306	585	7
*267	508	0	307	594	32
*268	509	0	308	594	32
269	509	17	309	594	32
270	509	17	310	594	32
271	516	98	311	598	24
*272	517	0	312	598	40
*273	517	0	313	598	40
274	517	34	314	598	24
275	517	34	315	598	40
276	517	34	316	598	40
277	517	34	317	598	40
278	517	34	318	598	40
279	517	34	319	598	40
280	517	34	320	598	40
			321	598	40

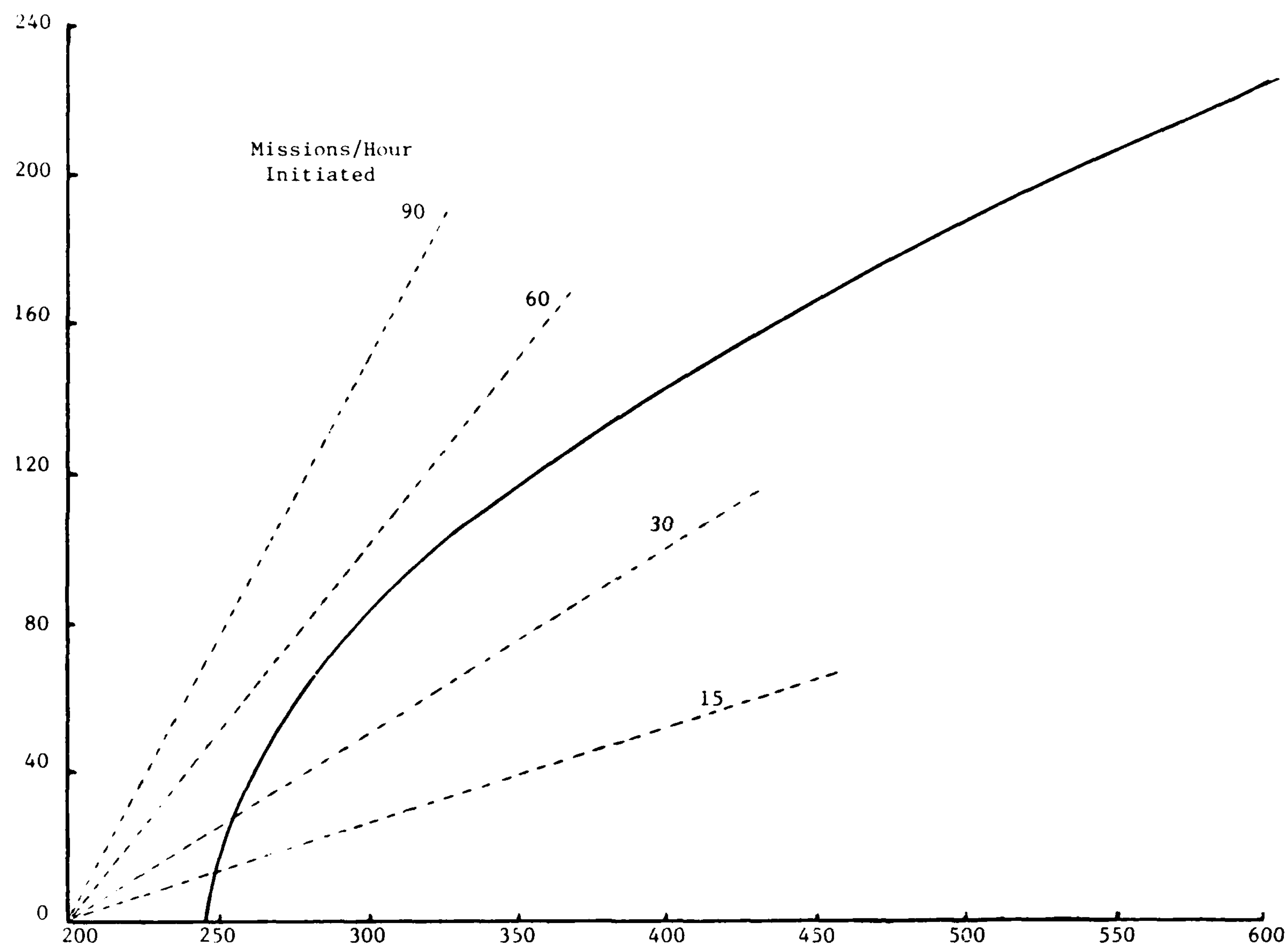

Figure 2. Mission Initiations Simulated in Both Models

messages are acknowledged. In order to provide suitable inputs to the BRLMPM, all acknowledgements had to be removed from the mission profiles (Tables 1 to 4) since the BRLMPM automatically generates acknowledgements to each message. The time to transmit each acknowledgement (390 bits) can then be calculated. In addition, for each transmission (message or acknowledgement), the net is tied up for a period longer than that necessary to transmit the message. When the transmit button is pushed, there is first a turn-on time for the radio net that averages 0.205 seconds.[6] Next, there is a net access delay time which is a delay between the time a message is projected into a net and the time the message is routed to its destination. The net access delay time averages 1.195 seconds. Finally, there is a message preamble which is a set of identifiers that characterizes the transmitter and assures that the following message is real rather than a decoy. The message preamble time averages 1.638 seconds.

The results of acknowledging all messages and including the turn-on, net access and message preamble delays in all transmissions were calculated and are shown in Table 8. It can been seen that the minimum possible mission duration (no message queues or failures) ranged from five to nineteen minutes in the BRLMPM depending on channel capacity and mission type and between 2 ½ and 12 minutes in the Norden model.

The pertinent information from Tables 7 and 8 was weighted by the frequencies of occurrence shown in Table 5. The results, now as a function of mix, are presented in Table 9. It is apparent that, for the given mixes of mission types, the minimum possible mission duration obtained with the Norden model (mix three) is 3.1 minutes as opposed to 5.4 minutes with the BRLMPM. More likely values resulted from using Mix 2 with a channel capacity of 1200 bits/sec for which the corresponding numbers are 6.3 minutes and 9.6 minutes respectively. The ability to complete a field artillery mission in this time is contingent upon two restrictions. First, none of the messages has to wait in a queue to be acted upon. Second, none of the messages fails and thus has to be repeated.

In reality, these restrictions are likely to be impossible to meet. First, as will be seen, the rate at which missions are initiated in this study (on the average, one mission every 94 seconds) assures that on the average at least three missions must be in progress simultaneously thus building up queues at choke points. Second, limited HELBAT 8 data indicates that a message failure rate of ten percent is likely. Based on these facts, it is apparent that these minimum possible actual mission durations must be revised upwards significantly.

It is apparent that certain units are more likely to be overloaded than others in processing a fire mission. One measure of the overloading likelihood is the numbers of communication links each unit is required to maintain. Another such measure is the number of messages and acknowledgements received by each unit type in performing a complete fire mission. These measures of the likelihood of overloading are presented in Table 10. The final column was based on an analysis of mission mix six which is composed of more nearly equal contributions from the four mission types than the other mixes. It is apparent from this table that the BNFDC and the battery FDCs are most likely to be the overloaded units in a realistic combat scenario. The Norden model constrains the number of fire missions that can be simultaneously processed to ten at the BNFDC and three at the battery FDC. There are no corresponding limits in the BRLMPM.

B. Comparison Between the Outputs of the Two Models

Results of runs made with the Norden Battery C^3 Model and the BRL Message Processing Model are shown in Tables 11 and 12. As before, "Mix" is defined by Table 5 and "Channel Capacity" is transmission rate in bits/sec. "Fraction Completed" is the ratio of missions completed to missions initiated and "Mean Duration" is the arithmetic average of the durations of all completed missions.

The FD (fire direction) net connects the three FISTs, the BNFSE, the BNFDC, and the Battery FDC. The GO (gun orders - unofficial usage) net connects the battery FDC with the individual howitzers. Three of each of these nets are needed to provide battalion fire support. "Entries" is the

TABLE 7. TRANSMISSION AND DELAY TIMES IN THE NORDEN MODEL

MISSION TYPE	NODAL DELAY (SEC)	TOTAL LENGTH (BITS)	TRANSMISSION TIME (SEC) 300 BITS/SEC	1200 BITS/SEC	4800 BITS/SEC	TOTAL TIME (MIN) 300 BITS/SEC	1200 BITS/SEC	4800 BITS/SEC
1	420.6	96250.	320.8	80.2	20.1	12.36	8.35	7.34
2	364.3	79516.	265.1	66.3	16.6	10.49	7.18	6.35
3	287.4	57942.	193.1	48.3	12.1	8.01	5.59	4.99
4	143.2	38824.	129.4	32.4	8.1	4.54	2.93	2.52

TABLE 9. TRANSMISSION AND DELAY TIMES IN THE BRLMPM

MISSION TYPE	NODAL DELAY (SEC)	TOTAL LENGTH (BITS) MSG	ACK	TOTAL	NO. OF MSG AND ACKS
1	455.6	94690.	18720.	113410.	96
2	361.8	77956.	12870.	90826.	66
3	317.4	57162.	10140.	67302.	52
4	175.7	38044.	5850.	43894.	30

MISSION TYPE	TRANSMISSION DELAY TIMES (SEC) TURN-ON	NET ACCESS	PRE-AMBLE	TOTAL
1	19.7	114.7	157.2	291.6
2	13.5	78.9	108.1	200.5
3	10.7	62.1	85.2	158.0
4	6.2	35.9	49.1	91.1

MISSION TYPE	TOTAL TRANSMISSION TIME (SEC) 300 BITS/SEC	1200 BITS/SEC	4800 BITS/SEC	TOTAL TIME (MINUTES) 300 BITS/SEC	1200 BITS/SEC	4800 BITS/SEC
1	669.7	386.2	315.3	18.75	14.03	12.85
2	503.3	276.2	219.4	14.42	10.63	9.69
3	382.3	214.1	172.0	11.66	8.86	8.16
4	237.5	127.7	100.3	6.89	5.06	4.60

TABLE 9. CHARACTERISTICS OF AN AVERAGE ARTILLERY MISSION FOR A GIVEN MIX OF MISSION TYPES

MIX	TOTAL NODAL DELAY (SEC) NORDEN	TOTAL NODAL DELAY (SEC) BRLMPM	TOTAL TRANSMISSION TIME (SECONDS) NORDEN 300	NORDEN 1200	NORDEN 4800	BRLMPM 300	BRLMPM 1200	BRLMPM 4800
1	359.5	393.0	270.4	67.6	16.9	556.0	318.1	258.7
2	322.3	331.1	233.6	58.4	14.6	446.2	245.6	195.4
3	176.4	208.3	144.1	36.0	9.0	270.8	147.6	116.9
4	226.2	254.9	176.8	44.2	11.0	340.6	188.3	150.2
5	286.0	310.9	216.0	54.0	13.5	424.3	237.1	190.3
6	329.8	352.8	245.2	61.3	15.3	487.8	274.4	221.1

MIX	NUMBER OF MSG. AND ACKS NORDEN	NUMBER OF MSG. AND ACKS BRLMPM	TOTAL MISSION DURATION (MINUTES) NORDEN 300	NORDEN 1200	NORDEN 4800	BRLMPM 300	BRLMPM 1200	BRLMPM 4800
1	42.6	78.6	10.50	7.12	6.27	15.82	11.85	10.86
2	32.7	58.8	9.26	6.34	5.61	12.96	9.61	8.78
3	19.5	35.1	5.34	3.54	3.09	7.98	5.93	5.42
4	25.0	45.3	6.72	4.51	3.95	9.92	7.39	6.75
5	31.6	57.5	8.37	5.67	4.99	12.25	9.13	8.35
6	36.7	66.9	9.58	6.52	5.75	14.01	10.45	9.56

number of times messages enter the proper queue (BNFDC queue for the FD net, battery FDC for the GO net) and "Util" is the fractional time utilization of the indicated net.

As was described earlier, both the Norden model and the BRLMPM are stochastic models. The amount of intrinsic variation to be expected in the outputs of the Norden model is unknown. The amount of intrinsic variation to be expected in the BRLMPM was estimated by running the model ten times under identical conditions while varying only the random number sequence that was employed. The results of this exercise are shown in Table 13. The condition simulated in this table is mission mix six at a channel capacity of 1200 bits/sec.

The coefficient of variation, which is the standard deviation of a data set divided by the mean, can be used as a measure of the relative dispersion among several sets of data that are of different orders of magnitude and measured in different units. It can be seen that the relative variations are greatest in the fraction of missions completed and the mean mission duration, which are the most important variables. The dispersion shown in Table 13 should be kept in mind to avoid a too-rigorous analysis of BRLMPM output trends.

The FD and GO net utilizations in both simulations are shown in Tables 14 and 15. The predicted time each net is in use is based directly on the amount of time it would be tied up in order to complete all the fire missions. The predicted mean time is (since there are three nets of each type) one-third of the predicted time. The predicted fraction of time is the predicted mean time divided by 5.88 hours. The modeled fraction of time are the FD and GO net utilizations shown in Tables 11 and 12.

To exemplify how these numbers were obtained, the various intermediate steps in the case of mix one, FD net, and 1200 bits/second are shown in Table 16. The first four lines in this table were obtained from an analysis of Tables 1-4, the results being weighted by the frequencies of occurrence given in Table 5.

Similar differences between predictions and simulations with both models are apparent in Tables 14 and 15. In both net types the net usages predicted are somewhat less than those resulting from the actual simulation. In the Norden model results, the sensitivity of the net usage to the channel capacity is obvious. In the BRLMPM predictions, the sensitivity to channel capacity is far less since the nets are tied up by events other than message transmission. In the BRLMPM simulations, the net usage is quite insensitive to channel capacity since more rapid message transmission opens up net time to repeat failed messages and reduces (but does not eliminate) the size of the queues.

The mission durations obtained in the two simulations are shown in Table 17. As can be seen, the Norden results are almost double the a priori predictions while the actual values obtained using the BRLMPM far exceed the predicted values. This feature can be easily explained by noting that queues develop at each node; queues were not considered in the predictions. The most restrictive queue is at the BNFDC. At the end of 5.88 hours, the BNFDC queue length averages 61 messages for the 18 conditions considered. For a message to advance through such a queue, to be processed, and the next message in the mission profile transmitted, there is a nonproductive delay of at least six minutes. Of course the queues are shorter at other nodes and are not as long at the BNFDC earlier in the engagement,but it is not surprising that, in view of the number of messages needed to process a field artillery mission, extremely long missions can result. Reducing the number of messages needed to perform a field artillery mission would be doubly beneficial in that not only would less time be required to transmit and process the needed messages, but the queue lengths would be sizably reduced, thus minimizing the nonproductive delays that result.

The fraction of missions completed in both models is shown in Table 18. The feature of most interest here is that there is a slight beneficial effect in increasing the channel capacity that is evident in both models. Again the Norden model is more optimistic than the BRLMPM, but not by drastic

TABLE 10. MEASURES OF UNIT OVERLOADING LIKELIHOOD

UNIT TYPE	NUMBER OF LINKS	MESSAGES SENT AND RECEIVED
FIST	3	0.86
BNFSE	5	1.33
BNFDC	15	18.88
BATT	7	18.16
GUNS	1	5.48

TABLE 11. RESULTS OBTAINED WITH THE NORDEN MODEL

MIX	CHANNEL CAPACITY (BITS/SEC)	FRACTION COMPLETED	MEAN DURATION (MIN)	FD ENTRIES	NET UTIL.	GO ENTRIES	NET UTIL.
1	300	0.47	22.5	1100	0.60	450	0.12
1	1200	0.62	16.5	550	0.20	750	0.17
1	4800	0.66	15.0	350	0.05	750	0.18
2	300	0.55	20.0	1000	0.58	150	0.12
2	1200	0.66	15.0	500	0.19	400	0.15
2	4800	0.81	13.5	350	0.04	450	0.15
3	4300	0.78	9.0	750	0.50	75	0.06
3	1200	0.83	6.0	450	0.13	100	0.07
3	4800	0.85	4.5	350	0.03	150	0.07
4	300	0.73	13.0	900	0.59	150	0.09
4	1200	0.81	8.0	450	0.17	250	0.10
4	4800	0.81	7.5	350	0.04	300	0.10
5	300	0.57	16.5	900	0.61	250	0.11
5	1200	0.72	12.5	500	0.18	400	0.14
5	4800	0.75	11.0	300	0.04	450	0.14
6	300	0.55	21.0	1000	0.61	300	0.12
6	1200	0.61	15.0	500	0.18	450	0.15
6	4800	0.70	13.5	350	0.04	600	0.16

TABLE 12. RESULTS OBTAINED WITH THE BRLMPM

MIX	CHANNEL CAPACITY (BITS/SEC)	FRACTION COMPLETED	MEAN DURATION (MIN)	FD ENTRIES	NET UTIL.	GO ENTRIES	NET UTIL.
1	300	0.29	167.6	958	0.98	1220	0.75
1	1200	0.27	187.0	1012	0.97	1311	0.79
1	4800	0.33	194.7	1034	0.97	1336	0.78
2	300	0.18	167.0	801	0.97	1532	0.88
2	1200	0.23	173.6	928	0.96	1469	0.89
2	4800	0.22	186.3	900	0.95	1422	0.85
3	300	0.68	116.9	753	0.92	966	0.55
3	1200	0.84	134.5	996	0.97	1033	0.57
3	4800	0.82	124.5	979	0.94	1008	0.55
4	300	0.52	146.5	937	0.97	1146	0.65
4	1200	0.59	139.0	1005	0.98	1240	0.66
4	4800	0.61	155.7	987	0.97	1196	0.65
5	300	0.40	151.8	955	0.97	1321	0.77
5	1200	0.44	155.1	999	0.97	1379	0.76
5	4800	0.45	143.0	981	0.97	1338	0.73
6	300	0.29	149.8	951	0.97	1372	0.78
6	1200	0.30	180.0	991	0.97	1449	0.83
6	4800	0.27	170.1	1004	0.97	1505	0.82

TABLE 13. TENFOLD REPLICATION OF THE BRLMPM

REPLICATION	FRACTION COMPLETED	MEAN DURATION (MIN)	FD ENTRIES	FD NET UTIL.	GO ENTRIES	GO NET UTIL.
1	.273	186.95	1012	.971	1311	.788
2	.300	179.95	1005	.975	1331	.826
3	.291	169.96	997	.972	1323	.790
4	.264	172.84	994	.965	1328	.795
5	.268	188.41	990	.972	1337	.807
6	.314	179.46	1013	.974	1329	.794
7	.264	175.23	1006	.969	1357	.804
8	.295	175.29	1004	.970	1363	.803
9	.282	174.18	999	.975	1353	.810
10	.327	171.17	1021	.975	1364	.826
MEAN	.288	177.34	1004	.972	1340	.804
STD. DEV.	.022	6.30	9.48	.0032	18.40	.0133
COEF. OF VAR.	.075	.036	.0094	.0033	.0137	.01655

TABLE 14. FD NET USAGE OF BOTH MODELS IN 5.88 HOURS OF BATTLE TIME

---------------------------NORDEN---------------------------

MIX	PRED. TIME NETS IN USE (SEC) 300	1200	4800	PRED. MEAN TIME NETS IN USE (SEC) 300	1200	4800
1	32082.	8021.	2005.	10694.	2674.	668.
2	29427.	7357.	1839.	9809.	2452.	613.
3	17428.	4357.	1089.	5809.	1452.	363.
4	21467.	5367.	1342.	7156.	1789.	447.
5	26313.	6578.	1645.	8771.	2193.	548.
6	29846.	7461.	1865.	9949.	2487.	622.

MIX	PREDICTED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800	MODELED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800
1	.505	.126	.032	.60	.20	.05
2	.463	.116	.029	.58	.19	.04
3	.274	.069	.017	.50	.13	.03
4	.338	.085	.021	.59	.17	.04
5	.414	.104	.026	.61	.18	.04
6	.470	.117	.029	.61	.18	.04

---------------------------BRLMPM---------------------------

MIX	PRED. TIME NETS IN USE (SEC) 300	1200	4800	PRED. MEAN TIME NETS IN USE (SEC) 300	1200	4800
1	63881.	35616.	28549.	21294.	11872.	9516.
2	54653.	29248.	22897.	18218.	9749.	7632.
3	33891.	18644.	14832.	11297.	6215.	4944.
4	41581.	22822.	18132.	13860.	7607.	6044.
5	50808.	27836.	22093.	16936.	9279.	7364.
6	57694.	31628.	25112.	19231.	10543.	8371.

MIX	PREDICTED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800	MODELED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800
1	1.006	.561	.450	.98	.97	.97
2	.861	.461	.361	.97	.96	.95
3	.534	.294	.234	.92	.97	.94
4	.655	.359	.286	.97	.98	.97
5	.800	.438	.348	.97	.97	.97
6	.909	.498	.395	.97	.97	.97

TABLE 15. GO NET USAGE OF BOTH MODELS IN 5.88 HOURS OF BATTLE TIME

NORDEN

MIX	PRED. TIME NETS IN USE (SEC) 300	1200	4800	PRED. MEAN TIME NETS IN USE (SEC) 300	1200	4800
1	28069.	7017.	1754.	9356.	2339.	585.
2	22441.	5610.	1403.	7480.	1870.	468.
3	14297.	3574.	894.	4766.	1191.	298.
4	17618.	4404.	1101.	5873.	1468.	367.
5	21603.	5401.	1350.	7201.	1800.	450.
6	24638.	6160.	1540.	8213.	2053.	513.

MIX	PREDICTED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800	MODELED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800
1	.442	.111	.028	.12	.17	.18
2	.353	.088	.022	.12	.15	.15
3	.225	.056	.014	.06	.07	.07
4	.277	.069	.017	.09	.10	.10
5	.340	.085	.021	.11	.14	.14
6	.388	.097	.024	.12	.15	.16

BRLMPM

MIX	PRED. TIME NETS IN USE (SEC) 300	1200	4800	PRED. MEAN TIME NETS IN USE (SEC) 300	1200	4800
1	60539.	35795.	29609.	20180.	11932.	9870.
2	45054.	25834.	21029.	15018.	8611.	7010.
3	26343.	14389.	11401.	8781.	4796.	3800.
4	34359.	19366.	15618.	11453.	6455.	5206.
5	43979.	25339.	20680.	14660.	8446.	6893.
6	51379.	29948.	24590.	17126.	9983.	8197.

MIX	PREDICTED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800	MODELED FRACTION OF TIME EACH NET IS IN USE 300	1200	4800
1	.953	.564	.466	.75	.79	.78
2	.709	.407	.331	.88	.89	.75
3	.415	.227	.180	.55	.57	.55
4	.541	.305	.246	.65	.66	.65
5	.693	.399	.326	.77	.76	.73
6	.809	.472	.387	.78	.83	.82

TABLE 16. DERIVATION OF TABLES 14 AND 15 FOR
MIX 1, FD NET, AND 1200 BITS/SECOND

FACTOR OF INTEREST	NORDEN	BRLMPM
NUMBER OF TRANSMISSIONS/MISSION	42.6	78.6
NO. OF TRANSM./MISSION ON FD NET	19.16	38.32
NUMBER OF BITS/MISSION	80202	94238
NUMBER OF BITS/MISSION ON FD NET	42777	50249
TIME TO TRANSMIT (SECONDS)	35.65	41.87
TRANSMISSION DELAY (SECONDS)	00.00	116.42
TOTAL TIME ON FD NETS (SECONDS)	35.65	158.29
MEAN TIME ON FD NET (SECONDS)	11.88	52.76
TOTAL TIME/FD NET (SECONDS)	2673.56	11871.75

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TABLE 17. MEAN MISSION DURATIONS OBTAINED WITH BOTH MODELS IN 5.88 HOURS OF BATTLE TIME

---NORDEN---

MIX	PRED. MISSION DURATION (MIN) 300	1200	4800	ACTUAL MISSION DURATION (MIN) 300	1200	4800
1	10.50	7.12	6.27	22.5	16.5	15.0
2	9.26	6.34	5.61	20.0	15.0	13.5
3	5.34	3.54	3.09	9.0	6.0	4.5
4	6.72	4.51	3.95	13.0	8.0	7.5
5	8.37	5.67	4.99	16.5	12.5	11.0
6	9.58	6.52	5.75	21.0	15.0	13.5

---BRLMPM---

MIX	PRED. MISSION DURATION (MIN) 300	1200	4800	ACTUAL MISSION DURATION (MIN) 300	1200	4800
1	15.82	11.85	10.86	167.6	187.0	194.7
2	12.96	9.61	9.78	167.0	173.6	186.3
3	7.98	5.93	5.42	116.9	134.5	124.5
4	9.92	7.39	6.75	148.5	139.0	155.7
5	12.25	9.13	8.35	151.8	155.1	143.0
6	14.01	10.45	9.56	149.8	180.0	170.1

amounts as observed in the mission duration since the battle duration is long compared with the mean mission duration.

C. Data Analysis

The fraction completed and mean mission duration data for Norden and the BRLMPM are graphically presented in Figures 3 and 4. Figure 3 represents the fraction completed data averaged over type of mix (which was treated as a dependent variable Y-the variable being estimated) versus transmission rate (which was treated as the independent variable X-the variable from which estimates were made). The graph clearly indicates that the Norden model completes more missions than the BRLMPM over the three transmission rates studied. The mean mission duration data, also treated as a dependent variable, was averaged over mix type and then plotted against transmission rate, again the independent variable, in Figure 4. It is not surprising that the BRLMPM produces much longer mission durations than Norden since mission duration and number of missions completed (Figure 3) should be highly correlated. Although each of the plots is represented by only three points, they served as an aid for visually examining the extent to which the independent variable, transmission rate, may be (separately) related to each of the dependent variables, fraction completed and mean duration, and choosing an appropriate model for estimation.

Overall the graphic presentation of the data suggested a logarithmic transformation of the independent variable, transmission rate. A linear regression model of the form.

$$\hat{Y} = B_o + B_1 \ln X + \epsilon$$

was chosen to describe the average relationship between transmission rate ($ln X$) and each of the dependent variables ($\hat{Y}$), which was either fraction completed or mean mission duration. In the above model, B_o and B_1 are constants referred to as regression coefficients that must be estimated as functions of the observed data. The error term ϵ is assumed to be normally distributed with a mean of zero and a variance of T^2 .

Once the regression coefficients were determined for all four data sets, a measure of the relative importance between $\hat{Y}$ and $ln X$ could be explained in terms of the relative variation of the $\hat{Y}$ values around the regression line and the corresponding variation around the mean of $\bar{Y}$. This measurement is called the sample coefficient of determination, r^2. The r^2 measures that follow pertain only to the sample of 18 observations each for the fraction completed and mean duration data. The following r^2 measures were calculated for the BRLMPM data: $r^2 = .054$ as a degree of association between mean duration and transmission time while $r^2 = .015$ for the fraction completed versus transmission rate. Thus about 5.4 percent of the variation in mean duration was explained by the regression model while 1.5 percent of the variation in the fraction completed data was explained by the same model. For Norden's mean mission duration the model explained 26.2 percent of the variation while the model for the fraction completed data explained only 5.6 percent of the variation within the data. The degree of association between the independent and dependent variable of each data set was to be too small to justify any conclusion that either the fraction completed or mean duration data is a function of the single independent variable, transmission rate.

Since only a small fraction of the observed variation was explained for by the two-variable regression model, the effect of the type of mix on the results was examined. The fraction completed data for both models was plotted (Figures 5-7) versus mix type with transmission rate being held constant across mixes. Both models appear to be quite sensitive to changes in type of mix, with both completing the most missions at mix three. Figures 8-10 are plots of the mean duration versus type of mix with transmission rate again held constant over mix type. In the Norden model, mean duration appears to be fairly insensitive to mix. However, the BRLMPM consistently drops at mix three, then in general

TABLE 18. FRACTIONS OF MISSIONS COMPLETED OBTAINED WITH BOTH MODELS TO 5.88 HOURS OF BATTLE TIME.

	FRACTION COMPLETED (NORDEN)			FRACTION COMPLETED (BRLMPM)		
MIX	300	1200	4800	300	1200	4800
1	.47	.62	.66	.29	.27	.33
2	.55	.66	.81	.18	.23	.22
3	.78	.83	.85	.68	.84	.82
4	.73	.81	.81	.52	.59	.61
5	.57	.72	.75	.40	.44	.45
6	.55	.61	.70	.29	.30	.27

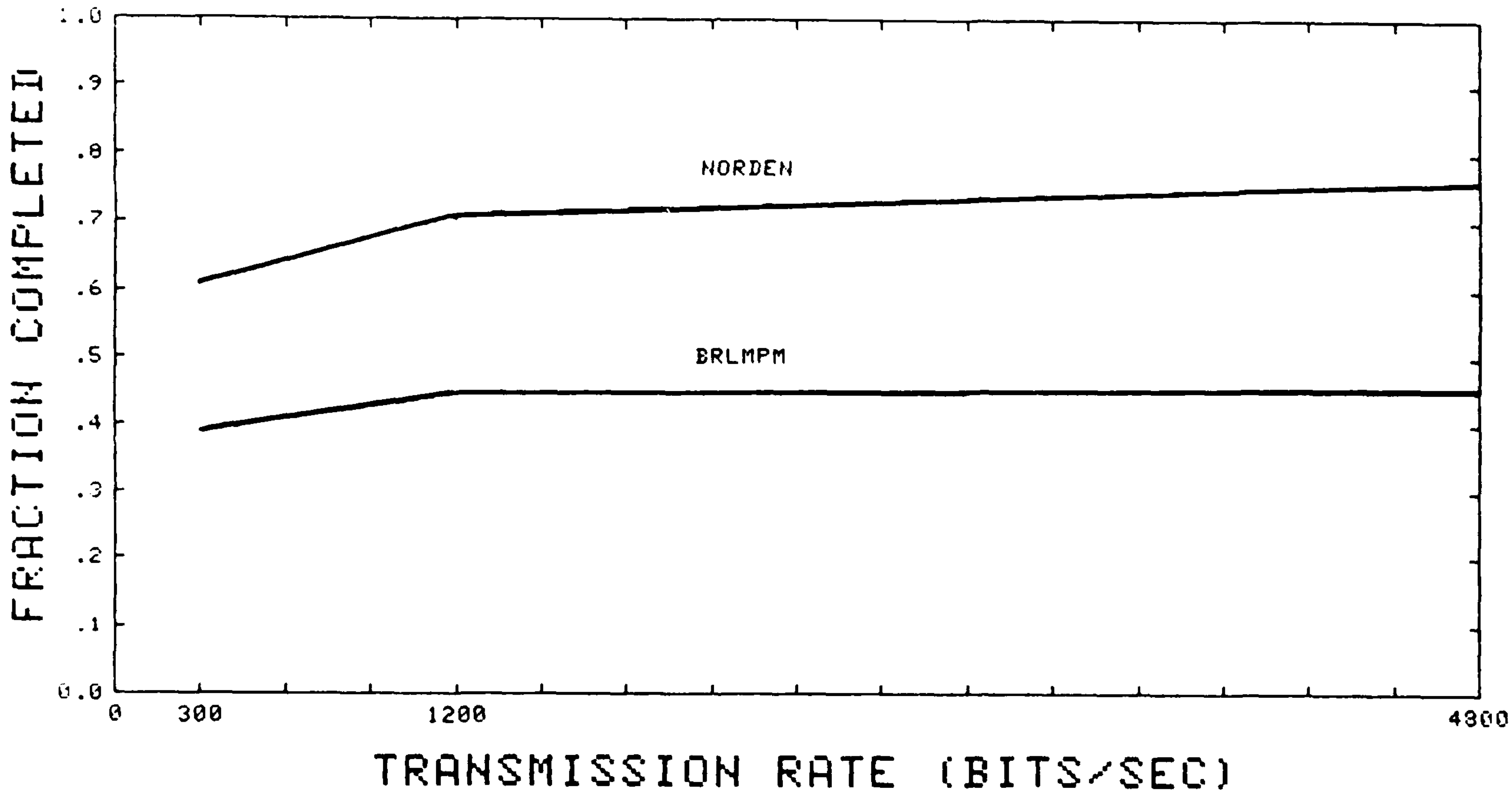

Figure 3. Average Fraction of Missions Completed as a Function of Transmission Rate

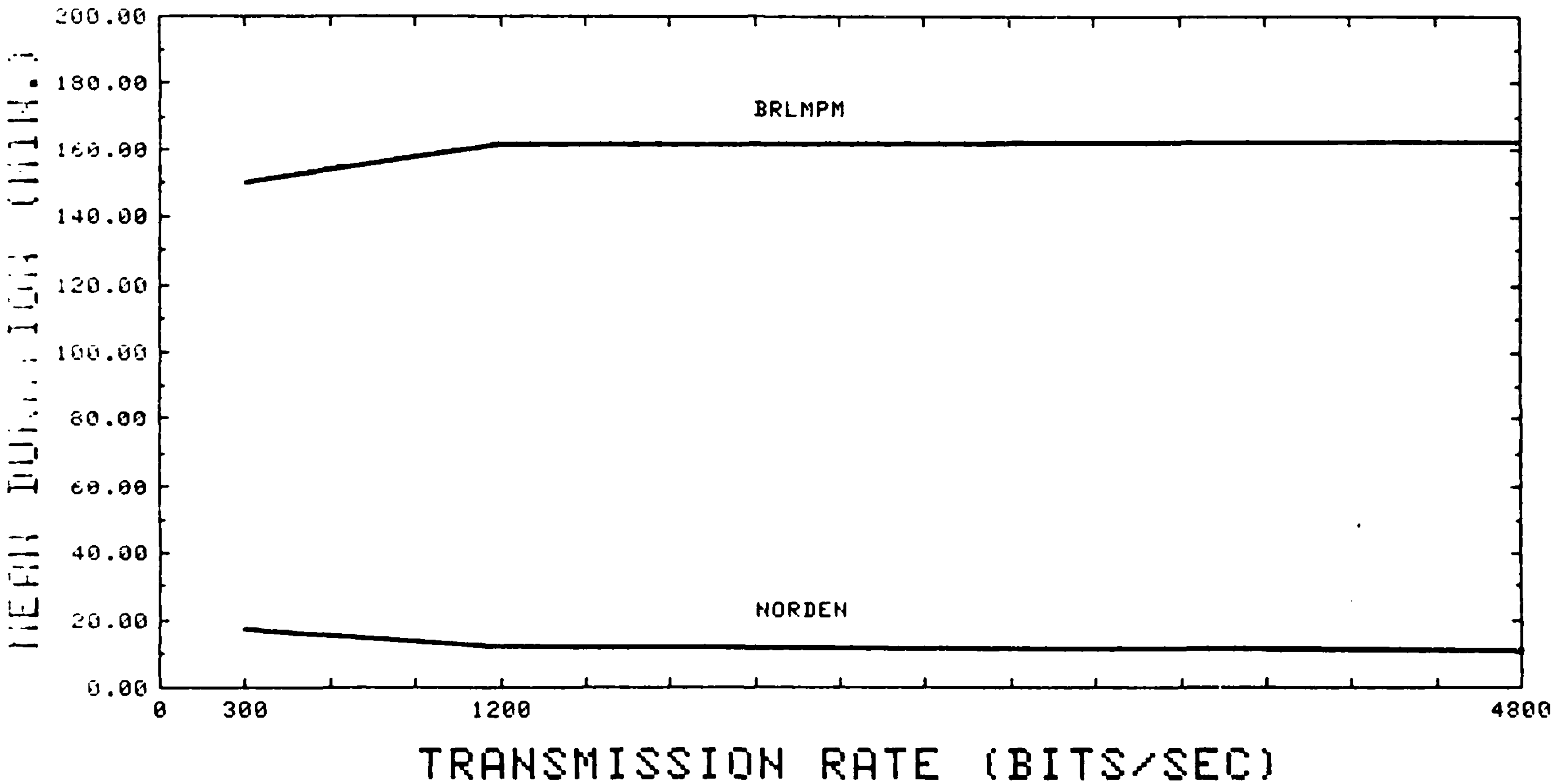

Figure 4. Mean Mission Duration as a Function of Transmission Rate

increases over mixes four through six. This drop at mix three is not unlikely since this mix has the smallest number of messages and acknowledgements needed to complete any one mission.

Before further attempting to model the BRLMPM and Norden data using transmission rate and mix type as independent variables, a two-way analysis of variance was performed on each data set. An analysis of variance is an analysis of the total variability of a set of data (as measured by the total sum of squares) into components which can be attributed to different sources of variation. The two-way analysis of variance allowed effects of mix type and transmission rate to be tested independently. It should be noted that since there was only one observation for each type of mix-transmission rate combination, no error sum of squares could be computed and the common error variance T^2 could not be estimated. In this special case it was not possible to assess whether an observed value of a mean square was significantly large or not because the usual standard of comparison, the error mean square, was not available. Under such circumstances, the usual procedure was followed, namely, to assume that any type of mix-transmission rate interaction was zero and to use the interaction mean square as the error mean square.

The analysis of variance tables for the data are presented in Tables 19-22. Column one of each table indicates the source of variation. Column two contains the numerical values of the sums of squares. The number of degrees of freedom is given in column three. The degrees of freedom are the number of independent pieces of information required to describe a particular source of variation in the model. Column four contains the numerical value of the mean square (equal to column two divided by column three) which is used in estimating T^2, the variance of the error term. The last column lists the mean square ratio (or calculated F) which was based on using the error mean square for the denominator.

For both the fraction completed and mean duration time data of the Norden model, the effects of mix type and transmission rate are significant at the .01 level. In the BRLMPM, type of mix is significant at the .01 level for both the fraction completed and the mean duration data. However, transmission rate is significant at the .05 level for the fraction completed data and is not significant at either of the tested levels for the mean duration data.

Based on the conclusions drawn from the analysis of variance performed on each data set, no further modeling was done since the sample size associated with each type of mix - transmission rate combination was only one. This restriction in sample size has made further statistical modeling impossible.

VI. EFFECT OF QUEUING ON THE BRLMPM MODELED MISSION DURATIONS

The BRLMPM modeled data were analyzed to determine how much of the total mission duration might be attributed to queuing. To perform such an analysis, expected mission durations for the BRLMPM had to be computed. The only other available data that would be useful were Norden's modeled mission durations. The question became whether or not the Norden modeled times would provide a suitable foundation from which to develop the BRLMPM expected mission durations. The answer to this question was provided by the predicted mission durations of both models.

The total predicted mission duration in the Norden model is a function of nodal delay time and message transmission time only; in the BRLMPM it is a function of nodal delay time, message transmission time and also message transmission delay time. Through a series of arithmetic manipulations, Norden's predicted mission duration for a particular mix and transmission rate was adjusted to (and, in fact, became equivalent to) the BRLMPM's predicted mission duration for the same mix-transmission rate combination. The following adjustments were made to Norden's predicted times:

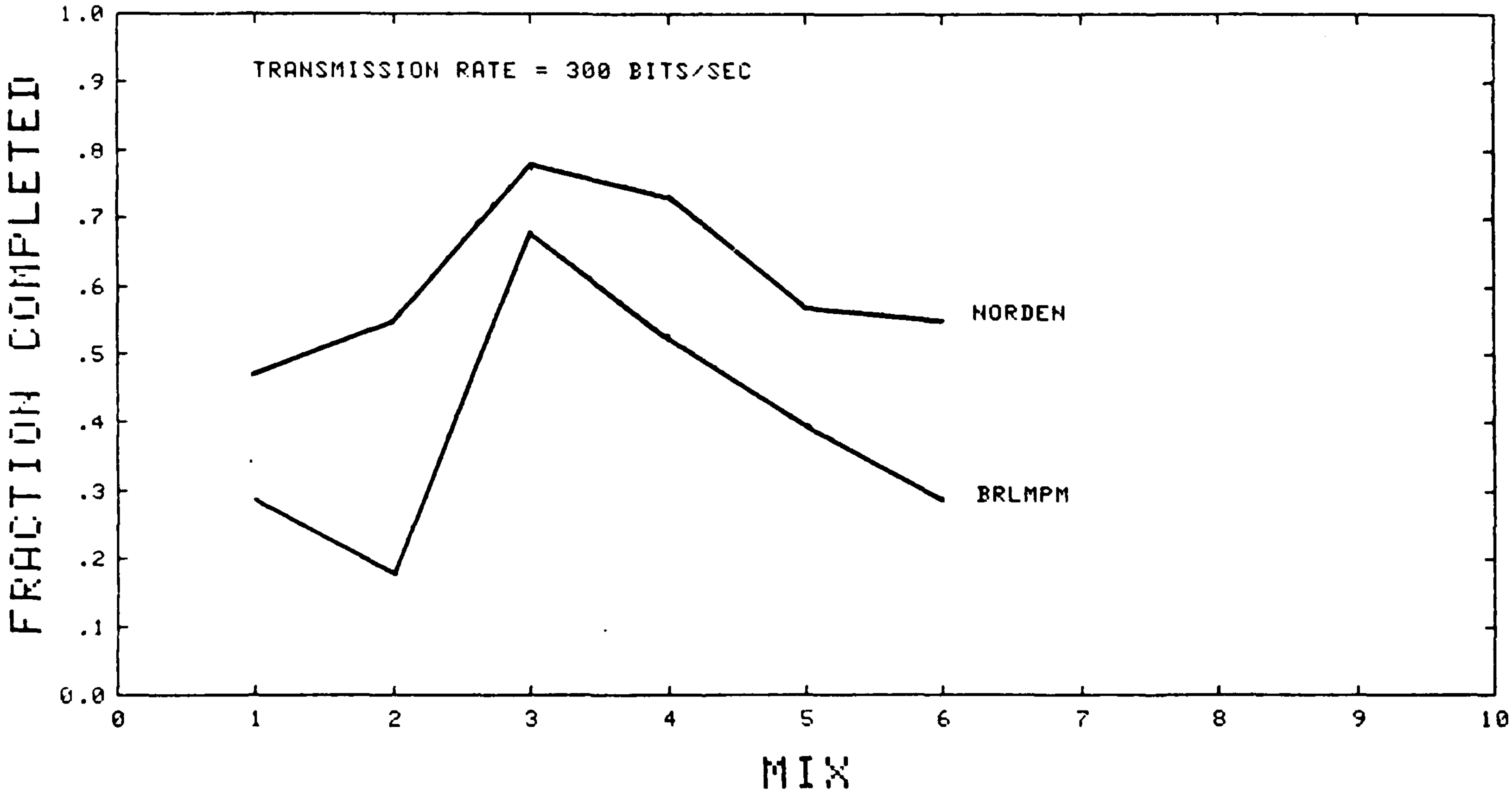

Figure 5. Fraction of Missions Completed as a Function of Mix for a Transmission Rate of 300 Bits/Second

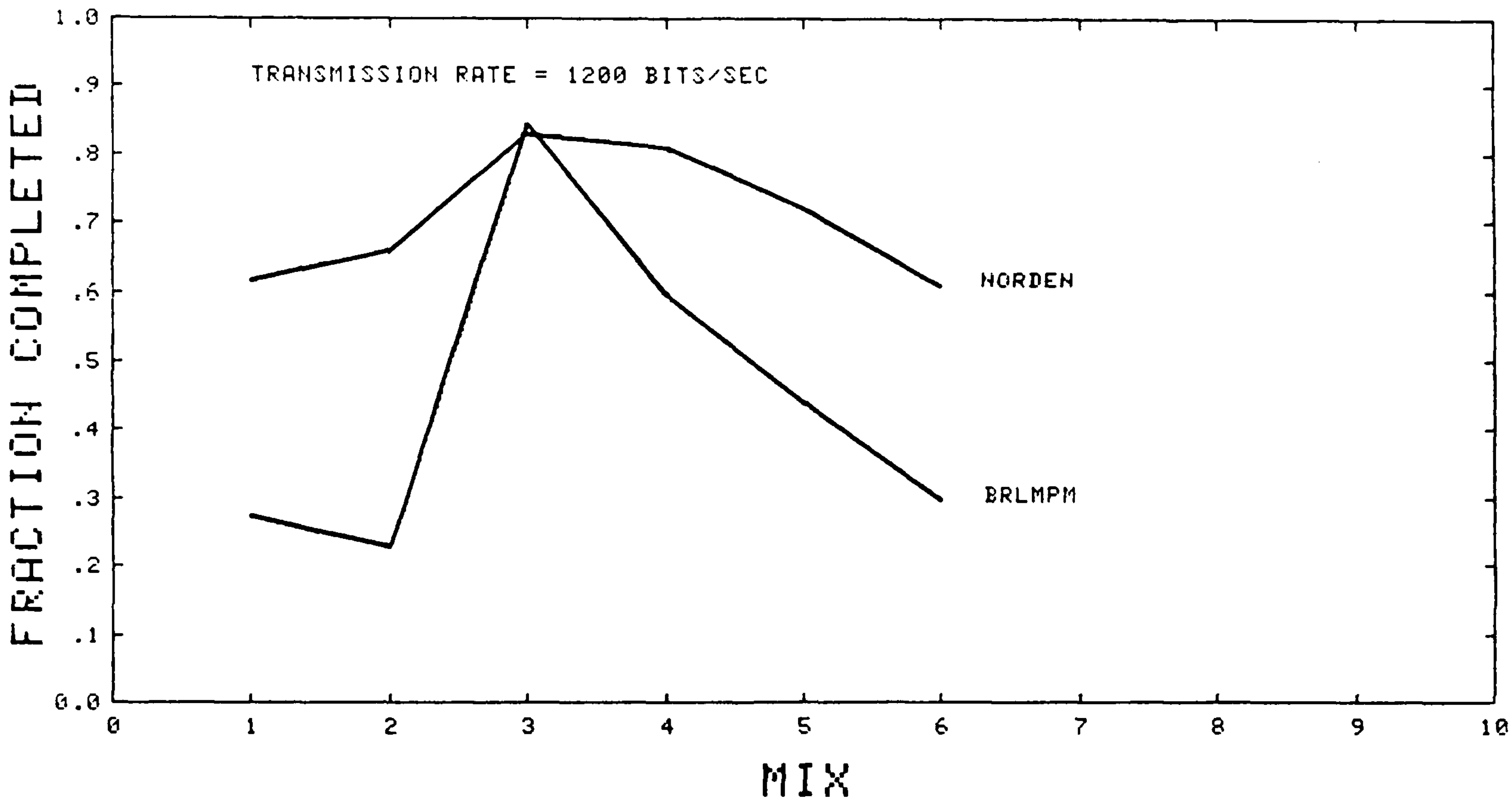

Figure 6. Fraction of Missions Completed as a Function of Mix for a Transmission Rate of 1200 Bits/Second

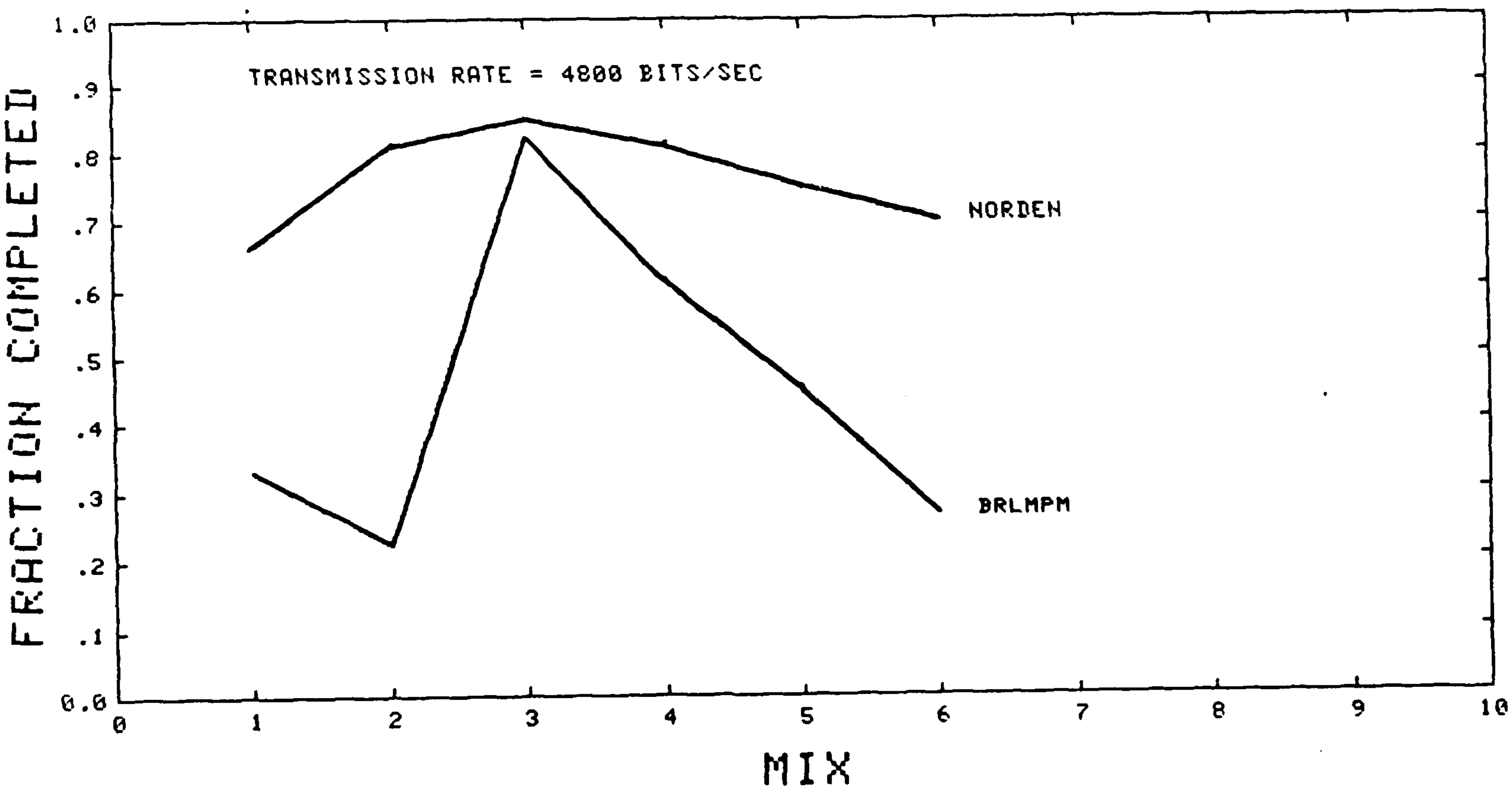

Figure 7. Fraction of Missions Completed as a Function of Mix for a Transmission Rate of 4800 Bits/Second

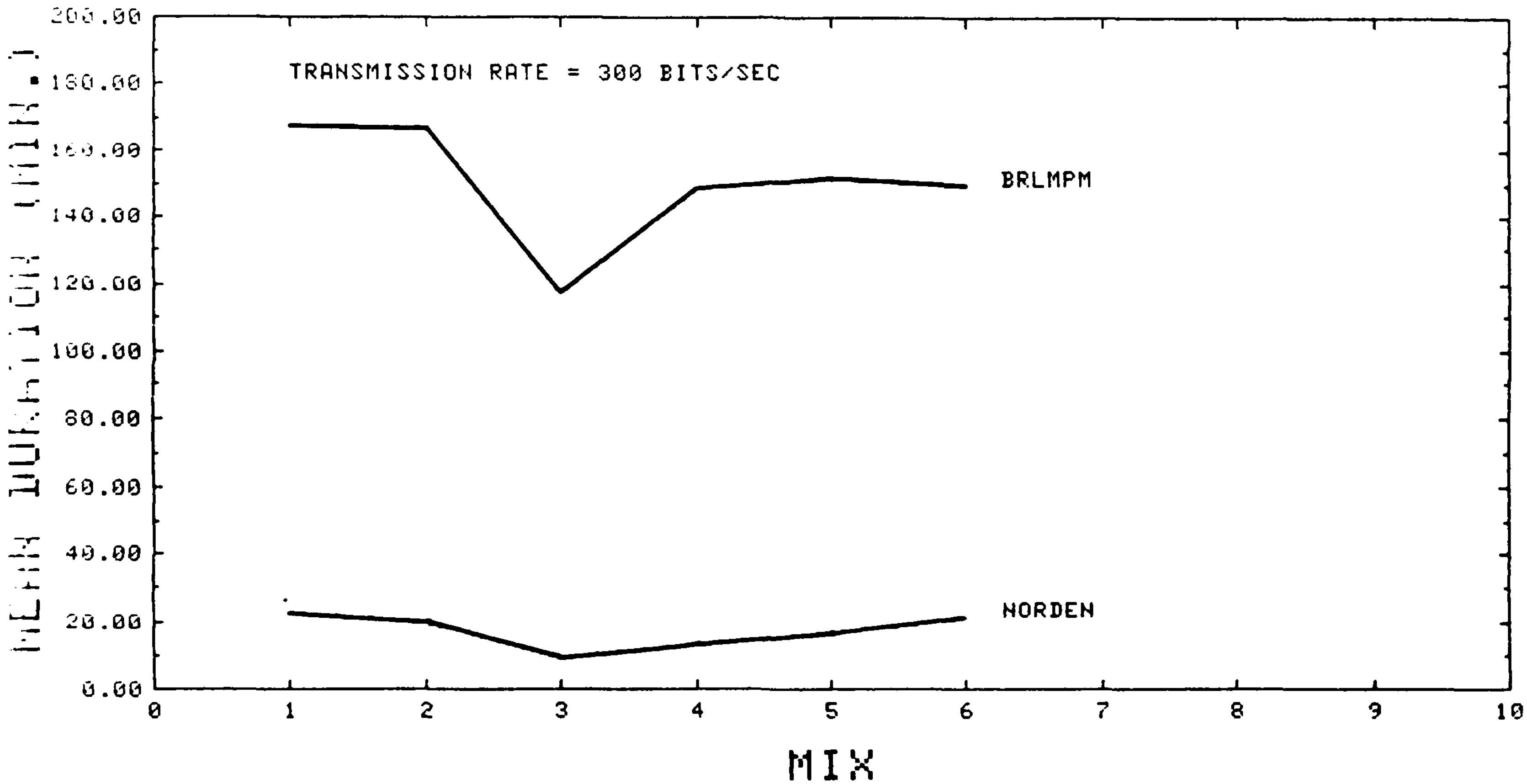

Figure 8. Mean Mission Duration as a Function of Mix for a Transmission Rate of 300 Bits/Second

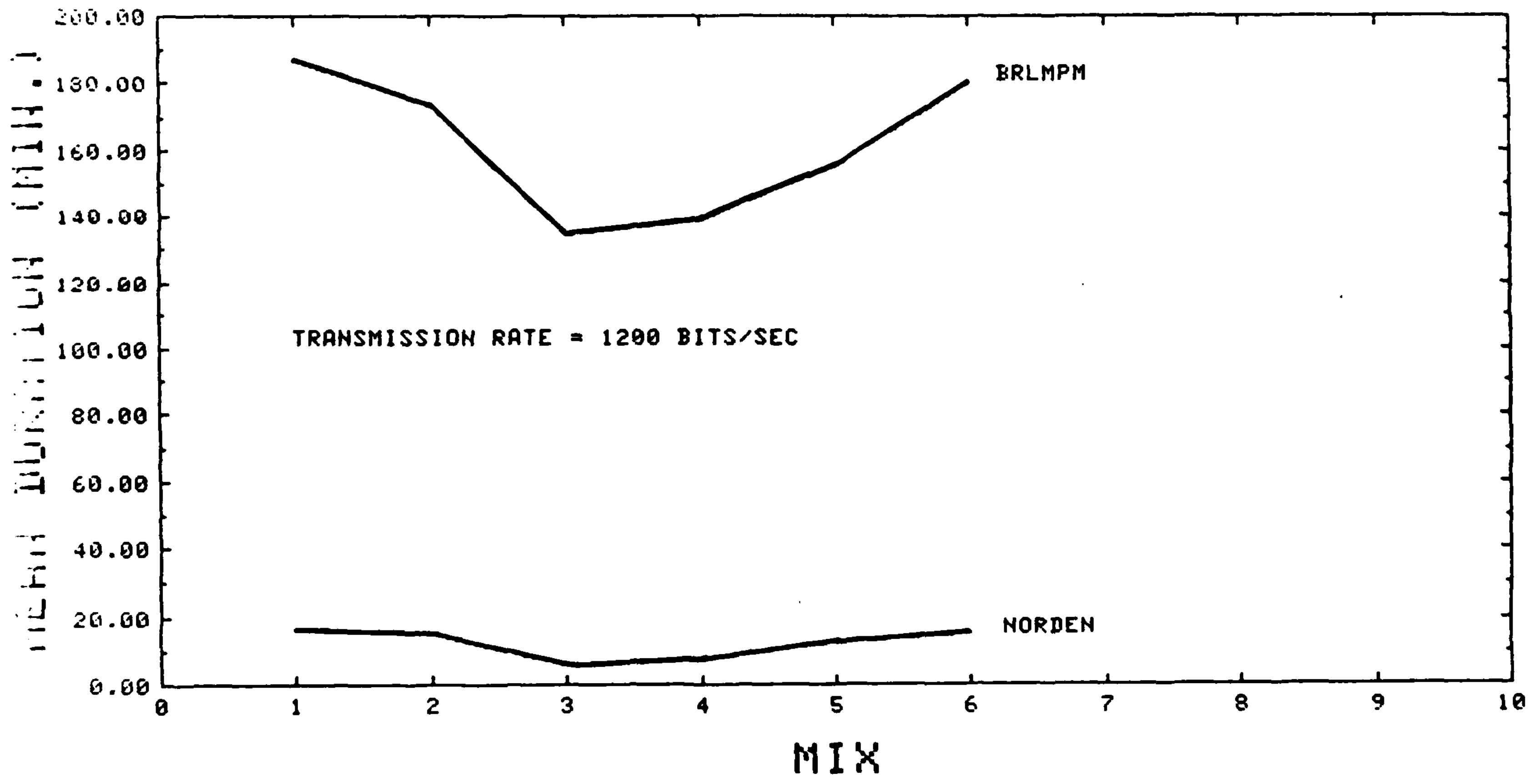

Figure 9. Mean Mission Duration as a Function of Mix for a Transmission Rate of 1200 Bits/Second

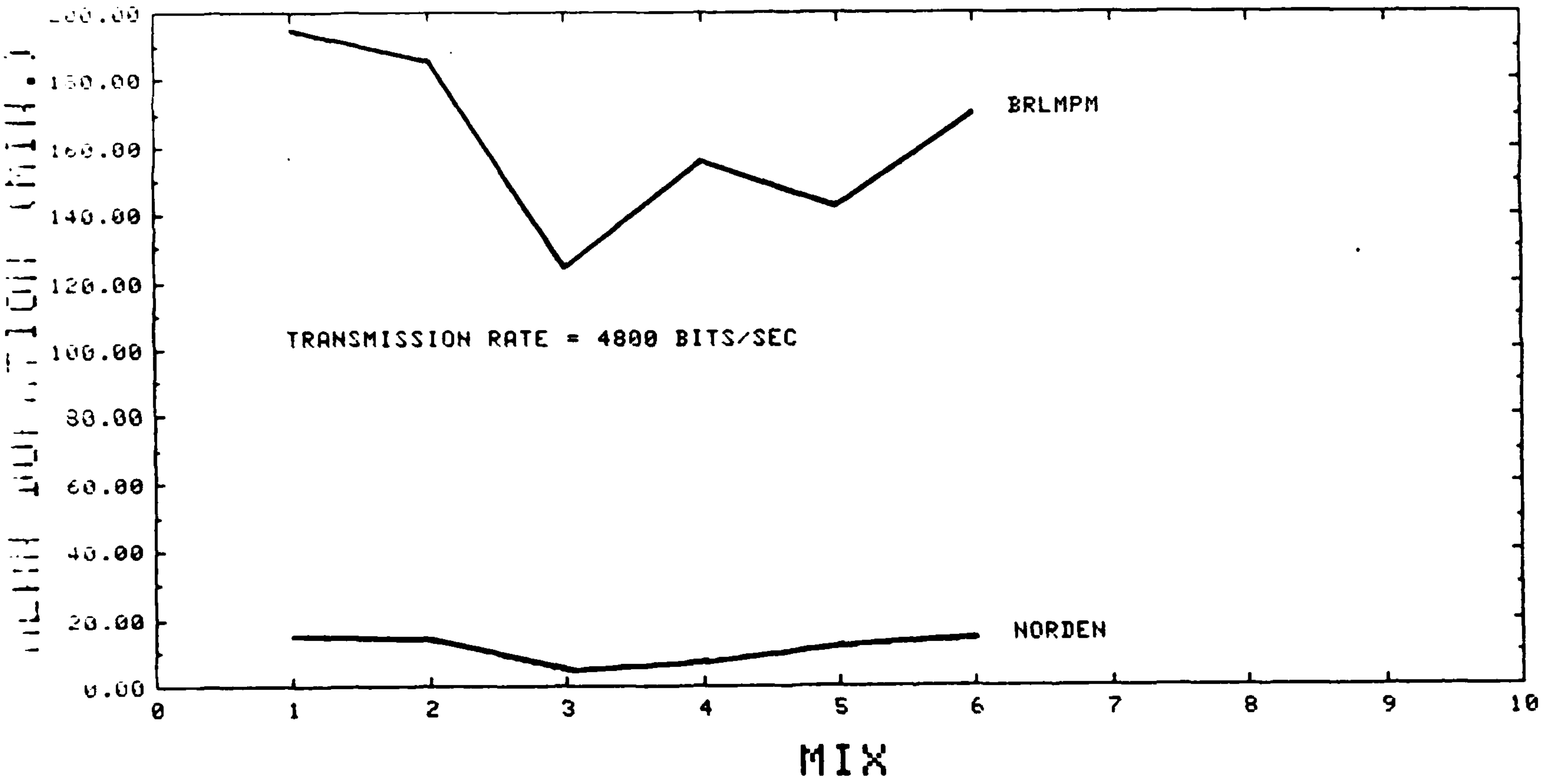

Figure 10. Mean Mission Duration as a Function of Mix for a Transmission Rate of 4800 Bits/Second

Table 19. Analysis of Variance Table for Fraction Completed in the Norden Model

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Mean Square Ratio
Treatments				
Mix	.12660	5	.02532	14.98225 *
Trans. Rate	.07410	2	.03705	21.92308 *
Error	.01690	10	.00169	
Total	.21760	17		

* Denotes significance at the 1% level

Table 20. Analysis of Variance Table for Mean Duration Time in the Norden Model

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Mean Square Ratio
Treatments				
Mix	303.66667	5	60.73333	121.46667 *
Trans. Rate	126.33333	2	63.16667	126.33333 *
Error	5.00000	10	.50000	
Total	435.00000	17		

* Denotes significance at the 1% level

Table 21. Analysis of Variance Table for Fraction Completed in the BRLMPM

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Mean Square Ratio
Treatments				
Mix	.68929	5	.13706	106.13601 *
Trans. Rate	.01181	2	.00591	4.54662 **
Error	.01299	10		
Total	.71409	17		

* Denotes significance at the 1% level
** Denotes significance at the 5% level

Table 22. Analysis of Variance Table for Mean Duration Time in the BRLMPM

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Mean Square Ratio
Treatments				
Mix	6764.05610	5	1352.81122	15.33836 *
Trans. Rate	548.94780	2	274.47390	3.11202
Error	881.97890	10	88.19789	
Total	8194.98280	17		

* Denotes significance at the 1% level

1. **The nodal delay time for a particular mix was increased (or decreased) to reflect the BRLMPM nodal delay time for the same mix (see Tables 7-8). Nodal delay time remained constant over all transmission rates within a particular mix.**

2. The mean mission duration for a particular mix was adjusted by the transmission time of the additional acknowledgements included in the BRLMPM for that mix. The difference in the total number of messages and acknowledgements (see Table 9) between the models for a particular mix is due to the fact that the BRLMPM acknowledges all messages and Norden acknowledges only gun orders. Since each acknowledgement has associated with it a word length of 390 bits, the transmission time of these extra acknowledgements varied across transmission rate within a mix.

3. The mission duration was adjusted by a transmission delay time comprised of a preamble time, equipment turn-on time, and net access delay time (see Table 9) associated with each message and acknowledgement of the BRLMPM. Since only time was involved in this calculation, the total amount of transmission delay time computed for a particular mix remained constant over all transmission rates within that mix.

Thus, the modeled Norden times provided a starting point in developing the BRLMPM expected mission duration times. Tables 23-25 outline the simple procedures needed to determine each of the adjustments to the Norden data. Examples are provided using a combination of mix one and a transmission rate of 1200 bits/second, but the adjustments for any mix - transmission rate combination may be computed using these procedures.

A breakdown of the BRLMPM expected mission durations is presented in Table 26. The differences between modeled and expected times are given in the last column and range from a minimum of 104.9 minutes to a maximum of 174.3 minutes. Table 27 presents the same data expressed in percentages. Between 82.7 percent and 94.3 percent of the variation between the expected and modeled times can be attributed to queuing and other unpredicted factors.

It seems unlikely that such large variations may be attributed to queuing alone. However, at this time, how much of the "unexplained" variation may be due to queuing would only be a best guess, and other factors which may possibly contribute to the variation have not been identified.

VII. CONCLUSIONS

Certain conclusions can be drawn from this study about the workings of both models. The Norden results are too optimistic since some aspects of the field artillery communications are not included in the model inputs. Tying up nets for the entire time needed for message transmission and acknowledging every message would change the Norden results significantly, not only directly, but also indirectly by adding nonproductive delays resulting from the development of nodal queues. Some aspects of the Norden simulations cannot be inferred directly from the referenced report (reference 4). For example, it is not clear whether dropped missions are included in calculating mission durations or mission completion rates. If they are not included, the Norden results are even more optimistic than would be the case if they are included.

The BRLMPM results are too pessimistic in that missions that are too "stale" to be fired profitably are not dropped, but add to the queues and delay the completion of more timely missions. The BRLMPM can and will be modified to permit dropping of missions whose durations exceed a specified threshold. An additional constraint applicable to TACFIRE but not modeled in the BRLMPM is that a maximum of 30 missions can be simultaneously handled by TACFIRE. No corresponding constraint exists in the BRLMPM at present; however it will be added in the near future. This problem was

Table 23a. Derivation of Nodal Delay Adjustment for Mix 1 at 1200 bits per second

BRLMPM Predicted Nodal Delay Time (sec)[1]	393.0	
Norden Predicted Nodal Delay Time (sec)[1]	-359.5	
Difference (sec)	33.5	
Norden Expected Nodal Delay Time (min)[2]		13.910
BRLMPM Fractional Increase Over Norden[3]		x .093
Nodal Delay Adjustment (min)		1.294 (1.3)

[1] See Table 9
[2] See Table 23b
[3] Line 3 divided by line 2

Table 23b. Derivation of Norden Expected Nodal Delay Time for Mix 1 at 1200 bits per second

Predicted Nodal Delay Time (sec)[1]	359.5	
Predicted Message Transmission Time (sec)[1]	66.8	
Total Predicted Mission Duration Time (sec)	426.3	
Total Modeled Mission Duration Time (min)[2]		16.500
Fractional Nodal Delay Time[3]		x .843
Modeled Nodal Delay Time (min)		13.910 (13.9)

[1] See Table 9
[2] See Table 11
[3] Line 1 divided by line 3

Table 24. Derivation of BRLMPM Transmission Delay Time for Mix 1

Message Preamble Time (sec)	1.638	
Radio Net Turn-on Time (sec)	0.205	
Net Access Delay Time (sec)	1.195	
Transmission Delay Time per Message (sec)		3.038
No. of Messages, including ACK's, for Mix 1 [1]		x 78.600
Total Transmission Delay Time for Mix 1 (sec)		238.787
Total Transmission Delay Time for Mix 1 (min)		3.980 (4.0)

[1] See Table 9

Table 25. Derivation of Transmission Time Only of the Extra ACKs of the BRLMPM for Mix 1 at 1200 bits per second

No. of ACKs in Mix 1 of the BRLMPM[1]	39.31	
No. of ACKs in Mix 1 of the Norden model [1]	-3.32	
Difference in no. of ACKs for Mix 1		35.99
Word length, in bits, of each ACK		x 390.00
Total word length, in bits, of the extra ACKs		14036.10
Total transmission time only of the extra ACKs (sec)[2]		11.70
Total transmission time only of the extra ACKs (min)		.19
		(.2)

[1] The number of ACKs included in either model for Mix 1 is the sum of the products of the number of ACKs for each mission type times its respective weighting factor (see Table 5):

Mix 1 of the BRLMPM: (48)(.66) + (33)(.00) + (26)(.23) + (15)(.11) = 39.31 ACKs

Mix 1 of the Norden Model: (4)(.66) + (4)(.00) + (2)(.23) + (2)(.11) = 3.32 ACKs

[2] Line 5 divided by 1200 bits per second

Table 26. Breakdown of Modeled BRLMPM Mission Duration (Minutes)

Mix	Norden Modeled Time	Nodal Delay Adj.	Trans Delay Time (BRLMPM)	Xtra Ack Trans Time (BRLMPM)	BRLMPM Expected Time	BRLMPM Modeled Time	Difference
1	22.5	1.2	4.0	.8	28.5	167.6	139.1
1	16.5	1.3	4.0	.2	22.0	187.0	165.0
1	15.0	1.3	4.0	.1	20.4	194.7	174.3
2	20.0	.3	3.0	.6	23.9	167.0	143.1
2	15.0	.3	3.0	.1	18.4	173.6	155.2
2	13.5	.4	3.0	.0	16.9	186.3	169.4
3	9.0	.9	1.8	.3	12.0	116.9	104.9
3	6.0	.9	1.8	.1	8.8	134.5	125.7
3	4.5	.8	1.8	.0	7.1	124.5	117.4
4	13.0	.9	2.3	.5	16.7	148.5	131.8
4	8.0	.8	2.3	.1	11.2	139.0	127.8
4	7.5	.9	2.3	.0	10.7	155.7	145.0
5	16.5	.8	2.9	.6	20.8	151.8	131.0
5	12.5	.9	2.9	.2	16.5	155.1	138.6
5	11.0	.9	2.9	.1	14.9	143.0	128.1
6	21.0	.8	3.4	.7	25.9	149.8	123.9
6	15.0	.9	3.4	.2	19.5	180.0	160.5
6	13.5	.9	3.4	.0	17.8	170.1	152.3

Table 27. Breakdown of Modeled BRLMPM Mission Duration (Percentages)

Mix	Norden Modeled Time	Nodal Delay Adj.	Trans Delay Time (BRLMPM)	Xtra Acks Trans Time (BRLMPM)	BRLMPM Expected Time	BRLMPM Modeled Time	Difference
1	13.4	.7	2.4	.5	17.0	100.0	83.0
1	8.8	.7	2.1	.1	11.7	100.0	88.3
1	7.7	.7	2.1	.0	10.5	100.0	89.5
2	12.0	.2	1.8	.3	14.3	100.0	85.7
2	8.6	.2	1.7	.1	10.6	100.0	89.4
2	7.2	.2	1.6	.0	9.0	100.0	91.0
3	7.7	.8	1.5	.3	10.3	100.0	89.7
3	4.4	.7	1.3	.1	6.5	100.0	93.5
3	3.6	.6	1.4	.0	5.7	100.0	94.3
4	8.8	.6	1.5	.3	11.2	100.0	88.8
4	5.8	.6	1.6	.1	8.1	100.0	91.9
4	4.8	.6	1.5	.0	6.9	100.0	93.1
5	10.9	.5	1.9	.4	13.7	100.0	86.3
5	8.0	.6	1.9	.1	10.6	100.0	89.4
5	7.7	.6	2.1	.0	10.4	100.0	89.6
6	14.0	.6	2.3	.4	17.3	100.0	82.7
6	8.3	.5	1.9	.1	10.8	100.0	89.2
6	7.9	.6	2.0	.0	10.5	100.0	89.5

confounded by the likelihood that when the BRLMPM was modified for this study by deleting the various existing delays to incorporate the nodal delays, one delay was overlooked. Even though the amount of the delay was small, the total number of messages processed was high and the delay at each node for each affected message was therefore several seconds longer than previously believed.

The point that must be stressed is that in TACFIRE as well as in the BRLMPM simulation, significant queues do develop. Some work with the BRLMPM subsequent to that described here indicates that even with perfect communications, mission initiation rates in excess of 40 missions/hr result in TACFIRE queues that increase without bound. Thus, the TACFIRE delays can increase significantly under conditions less severe than those addressed in this study. In the real world, however, perfect communications do not exist. In the baseline BRLMPM, it is assumed that any message can be nonacknowledging (NAKed), thus requiring re-transmission. If the same message is NAKed four times, an event of probability 0.01, the sending unit is removed from the subscriber table resulting in a down time of 30 minutes. If this criterion was applied to the scenario described in this report using mission mix one, the number of messages that must be processed to complete all missions is 226 missions x 78.6 messages/mission (Table 9) = 17,763 messages. Thus 177 times, a unit will be shut down for a sizable time. If the affected unit is FO, only the missions he is handling will be affected. If, however, the affected unit is a battery or a BNFSE, one-third of the missions currently being processed will be subject to long delays. It is not surprising that mission durations exceeding one hour would result.

Finally, it is felt that many of the data inputs to the Norden model (e.g., networks, mission profiles, and delays) are realistic. For strict realism, some of the fire missions should be started by forward observers rather than FISTs and informational messages should be sent to the brigade fire support officer (BDEFSO) and division artillery (DIVARTY); but as these nets are not heavily used the results probably would not change drastically. On the other hand, the method used to process the messages is inadequate. The Norden model should be revised so as to insure acknowledging each message. In addition, turn-on-time, net access delay time, and preamble time should be included in a realistic manner for each message and acknowledgement. If these modifications are made, the Norden model should be a useful tool for DSWS analyses.

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