NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

A SYSTEMS EVALUATION APPROACH TO ANALYSIS OF TACTICAL TIC-TAC-TOE (T4) GENERATED DATA

by

Eugene M Zarrillo

June, 1993

Thesis Co-Advisors: Michael G. Sovereign
Gary Porter

Unclassified
Security Classification of this page

REPORT DOCUMENTATION PAGE

1a Report Security Classification: Unclassified		1b Restrictive Markings	
2a Security Classification Authority		3 Distribution/Availability of Report Approved for public release; distribution is unlimited.	
2b Declassification/Downgrading Schedule			
4 Performing Organization Report Number(s)		5 Monitoring Organization Report Number(s)	
6a Name of Performing Organization Naval Postgraduate School	6b Office Symbol 39	7a Name of Monitoring Organization Naval Postgraduate School	
6c Address (city, state, and ZIP code) Monterey CA 93943-5000		7b Address (city, state, and ZIP code) Monterey CA 93943-5000	
8a Name of Funding/Sponsoring Organization	6b Office Symbol (if applicable)	9 Procurement Instrument Identification Number	
Address (city, state, and ZIP code)		10 Source of Funding Numbers Program Element No / Project No / Task No / Work Unit Accession No	
11 Title (include security classification) A SYSTEMS EVALUATION APPROACH TO ANALYSIS OF TACTICAL TIC-TAC-TOE (T4) GENERATED DATA (Unclassified)			
12 Personal Author(s) Eugene M. Zarrillo			
13a Type of Report Master's Thesis	13b Time Covered From To	14 Date of Report (year, month, day) 1993, June, 17	15 Page Count 74
16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
17 Cosati Codes Field / Group / Subgroup		18 Subject Terms (continue on reverse if necessary and identify by block number) T4, MOV, ANOVA, Tukey, P(W,, TTT, C3, C.L.T, MOE	

19 Abstract *(continue on reverse if necessary and identify by block number)*

The purpose of this thesis was to design, conduct, analyze and report the results of a C3 experiment. The T4 Simulation, acting as a surrogate for a C3 system, was used to generate data for statistical analysis. The objective was to determine which factors, and which factor levels, effected the MOE. As a result, the optimal *system alignment* was determined which would result in maximum values for the MOE.

The factors investigated were Area, Communication, and Tactical Delay, and probability of winning a same turn conflict, P(W). The levels of delay varied from zero to nine moves while levels for P(W) varied from zero to one in increments of one tenth.

Analysis showed that only two levels of Tactical Delay, zero and one, significantly changed the MOE. Analysis also showed that the player with the higher value of P(W), regardless of Tactical Delay, achieves a positive MOE. Therefore, the optimal *system alignment*, under the constraints of the experimental design, would be to assign P(W) = 1.0 to one side, while assigning the maximum value of delay to the other. Thus, this game configuration would maximize the MOE.

20 Distribution/Availability of Abstract _x_unclassified/unlimited ___ same as report ___ DTIC users	21 Abstract Security Classification Unclassified	
22a Name of Responsible Individual Michael G. Soveriegn	22b Telephone (include Area Code) (408) 656-2428	22c Office Symbol OR/SM

UNCLASSIFIED

Approved for public release; distribution is unlimited.

A Systems Evaluation Approach
to Analysis of Tactical Tic-Tac-Toe (T4)
Generated Data

by

Eugene M. Zarrillo
Lieutenant , United States Navy
B.S., Old Dominion University

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS TECHNOLOGY

from the

NAVAL POSTGRADUATE SCHOOL
June 1993

Author: Eugene M. Zarrillo

Approved by: Michael G. Sovereign, Thesis Co-Advisor

Gary Porter, Thesis Co-Advisor

for Paul H. Moose, Chairman
Command, Control and Communications Academic Group

ABSTRACT

The purpose of this thesis was to design, conduct, analyze and report the results of a C3 experiment. The T4 Simulation, acting as a surrogate for a C3 system, was used to generate data for statistical analysis. The objective was to determine which factors, and which factor levels, effected the MOE. As a result, the optimal *system alignment* was determined which would result in maximum values for the MOE.

The factors investigated were Area, Communication, and Tactical Delay, and probability of winning a same turn conflict, P(W). The levels of delay varied from zero to nine moves while levels for P(W) varied from zero to one in increments of one tenth.

Analysis showed that only Tactical Delay effected the MOE and that only two levels, zero and one, of Tactical Delay significantly changed the MOE. Analysis also showed that the player with the higher value of P(W), regardless of Tactical Delay, achieves a positive MOE. Therefore, the optimal *system alignment*, under the constraints of the experimental design, would be to assign P(W) = 1.0 to one side, while assigning the maximum value of delay to the other. Thus, this game configuration would maximize the MOE.

TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

The joint Command, Control and Communications (C3) curriculum is designed to provide a comprehensive operational and technical understanding of the field of C3 systems as applied to military operations. Students are introduced to modeling, systems architecture and engineering, and evaluation of C3 systems along with a basic knowledge of the physical principles and technologies that comprise communications systems, computers and sensors. The joint C3 curriculum includes instruction in communications and sensors, information science and tactical analysis/operations research that supports C3 systems development [Ref. 1: p. 66].

B. PURPOSE

This thesis concentrates in the area of C3 systems evaluation. The Naval Postgraduate School (NPS) offers a course in C3 systems evaluation primarily intended for students in the C3 curriculum.

> The course is designed to be one of the curriculum's capstone courses. C3 experiments related to the C3 evaluation process are conducted during the laboratory portion of the course. [Ref. 2:p 2]

The C3 systems evaluation course uses experiments involving simulations and wargames to help evaluate systems effectiveness. Typically, we evaluate, compare or test hypothesis about C3 systems or modifications to them. C3 systems evaluation allows the student to learn through experience how to design, conduct, analyze and report the results of C3 experiments. This thesis will utilize a simple game for the purpose of planning and conducting an experiment including hypothesis development, design of experiment, conduct of trials, collection and analysis of data and reporting of the results.

An enhanced version of the Tic-Tac-Toe (TTT) game called Tactical Tic-Tac-Toe (T4) was developed by Gary Porter to fulfill the need for the first experiment in the C3 Systems Evaluation course. It is used because it:

1. is easy to learn,
2. is new to all subjects,
3. is a non-military game, and
4. generates data that are C3 related.

T4 is a two-sided game. Players are assigned missions to achieve and their score is based on how well they achieve them. Players can play individually against an individual opponent or can be in teams of two playing against other teams of two. Missions are either to defeat or tie your opponent in the assigned game board (mission) area.

Mission effectiveness depends on the degree to which you have achieved your assigned mission. A victory mission requires that you score more TTTs in the assigned mission areas than your opponent. While a survival mission requires you to at least tie your opponent in the assigned mission area in order to achieve your mission. Mission success is based on the total number of TTTs achieved in an assigned mission area relative to your opponent.

When large amounts of experimental data are required, using human subjects to play T4 and to collect the data is time consuming and error prone. To alleviate these problems, Porter wrote the T4 Simulation which simulates human play, generates a wealth of data and collects the data for analysis. The data generated enable the user to statistically study how different inputs into the T4 game, the surrogate for a C3 system, effect mission outcome.

1. Research Questions

The course in systems evaluation referred to earlier is a C3 course appropriately called C3 Systems Evaluation. The course requires students to participate in and lead an experiment that uses either wargames or simulations to generate data for analysis. It is in this course that students are exposed to the T4 simulation. The course is not long enough for students to pursue a lengthy experiment. Thus, many of the questions a student may want to attempt to answer may not be considered. It is for that reason this thesis is being written.

This thesis will investigate how the T4 simulation responds to different types of intelligence delays. The delays will be investigated at several levels. The effect of changing the probability of winning a same turn conflict, P(W), will also be investigated. Finally, this thesis will investigate the effect delay and P(W) combined have on mission outcome. The following research questions will be answered using data generated as a result of multiple T4 replications:

1. As delay levels increase, mission margins of victory, MOVs, decline. Is there a level of delay above which further increases have no further effect on mission MOV?

2a. Does changing the probability of winning a same turn conflict, P(W), effect MOV?

2b. As the level of P(W) decreases, is a level reached beyond which P(W) has no effect on MOV?

3. Does changing the probability of winning a same turn conflict, P(W), effect mission outcome regardless of Time Delay?

4. Does an interaction exist between Time Delay and P(W)?

These research questions require some discussion so the reader is clear on exactly what is to be accomplished in this thesis. Mission outcome refers to the number of TTTs that a team scores. Relative to the opponents TTTs, this difference in scoring is referred to as the MOV. As intelligence delays are increased for a particular side, it is expected that the number of TTTs scored by that side will decrease. However, it is possible that beyond a certain level of delay, the number of TTTs will not continue to decrease but will level off at some value. Delays are discussed in greater detail below.

Conflict resolution is also described in detail below. So for now it will just be said that during T4 games, because of the simultaneous move rule, it is possible for two opposing players to attempt to enter the same game cell on the same move. Since only one player is allowed to occupy a cell, a conflict results. In the past, these conflicts were resolved randomly with both sides assigned the same probability of winning, P(W) = 0.5. The game now allows the probabilities to be weighted favoring a particular player. The thesis will evaluate the mission outcomes when one side is assigned a greater P(W) than the other side.

The MOV for the different P(W)-Time Delay combinations may indicate that P(W) for example, has no effect on MOV at some levels of Time Delay but has a significant effect at others. These P(W)-Time Delay combinations that significantly effect MOV are called interactions and the data will be analyzed to see if any exist.

The reader may not be able to adequately understand the posed questions until a discussion of T4 is presented. A thorough presentation of T4 is provided below. It begins by describing the simplest of the many T4 variants, the T4 Baseline game, and finishes with an explanation of the T4 Simulation. After the reader understands the T4 game better, it is suggested that the above Research Questions subsection be reread.

2. Approach

T4 simulation was used to generate the data that was analyzed to answer the above research questions. The first question was addressed in a previous thesis by Jeffrey S. Richardson. Richardson hypothesized that as time delay levels increase, mission outcome would decrease up to a point beyond which further increases would have no effect on mission outcome. While Richardson's data showed a significant relationship between Tactical Delay levels of zero and one, it failed to show that further increases, at some point, would have no effect on mission outcome. In fact, his data showed very little relationship between an increase in time delay and mission outcome. It is believed though, that there is a delay value above which mission outcomes no longer decline, but the number of replications of the T4 simulation used in Richardson's thesis

(30 replications per trial configuration) was insufficient to show this. Richardson's experimental design will be used to answer question one using 120 replications instead of the 30 that he originally used. If levels of delay are found beyond which mission accomplishment ceases to decline, then those greater delays will be omitted from this thesis in order to more fully concentrate on the remaining research questions.

The remaining research questions required a change in the T4 software to allow the user to input different levels of probability for same turn conflict resolution. Before the software change, when same turn conflict was resolved randomly, each side had the same probability of winning the conflict. To answer the second research question, this thesis investigated what would happen if one side had a higher probability of winning a same turn conflict. The data generated to answer Question 2 was used to answer the remaining research questions.

C. TACTICAL TIC-TAC-TOE (T4)

1. T4 Baseline

Several variants of T4 exist but it is not necessary to discuss all of them in order to understand the game. In the next few sections, variants that will enable the reader to understand the version of the game used with the thesis will be discussed. The T4 Baseline game is the most fundamental of all the versions and will provide the reader with a good foundation to understand the T4 game variant used in this thesis, T4 Simulation. The T4 Baseline game is very similar to the well known game of Tic-Tac-

Toe (TTT) and it uses the same three cell by three cell game board. The differences will be explained below.

a. Simultaneous Moves

Both players announce their moves simultaneously and plot them on the game board.

b. Conflict Resolution

Because moves are made simultaneously, there is a good possibility that both players will chose the same cell. When this occurs, it is called a same turn conflict and the winner is chosen randomly, flipping a fair coin. The winner remains in the cell while the loser is not allowed an alternate move and simply loses that turn. A variant of this game alternates same turn conflict resolution between players after the first conflict is decided randomly.

c. Scoring

Unlike the game of TTT, T4 does not end when the first TTT occurs. Instead, T4 is played until all nine cells are filled. When the game board is filled, the player with the most TTTs wins and is awarded one point. Recall there are eight possible ways to make a TTT (three horizontal, three vertical, and two diagonal). It is possible for a player to get all eight TTTs if every move results in a conflict and the same player wins every conflict.

2. T4 With Intelligence Delay Factor

This version is the same as the baseline game except for the addition of an enemy information delay factor. This factor, delays knowledge of opponents moves. The level of delay can be varied from zero to nine moves. The delay level is assigned before the game starts and can be set at the same or different levels for both players. When intelligence delay is introduced into the game, another type of conflict occurs and is termed a different turn conflict.

A player that is assigned a one move intelligence delay, for example, will not know which cell the opponent moved into until the following move. Therefore, it is possible the player assigned a delay may choose a cell that is already occupied. When this occurs, the conflict is always won by the player first occupying the cell. Like the baseline game, the loser is not allowed an alternate move and loses that turn.

3. Double Game Board T4

This version uses two TTT boards to form one larger board three cells high and six cells wide. Although it is considered only one board, the sides are designated as left and right game boards. In this game a turn consists of each player making a move on both the left and right game boards. These moves, like the baseline game are made in secret and announced simultaneously. Likewise, same and different turn conflicts are resolved as in the baseline game.

a. Crossover Scores

Unique to the double game board version are TTTs that cross from one game board side to the other. These are called crossover TTTs and there are ten possible ways for these to occur. Realize they can only occur horizontally or diagonally but not vertically.

b. Intelligence Delays

Like the T4 with Intelligence Delay game, the double game board version permits intelligence delays of zero through nine. Different delay levels are player independent. Different delay levels are also game board-side independent in that different delay levels may be assigned to different sides of the game board. All four players can be assigned different values of delay. For example, the X player on the left game board may have no intelligence delay while the right game board X player has an intelligence delay of several moves.

c. Mission Assignments

The assignment of missions in this version allows players to achieve an objective within a specific area of the game board. The objective assignments are either victory or survival. Victory is achieved by scoring more TTTs than an opponent in an assigned mission area while survival is achieved by either scoring a victory or tieing an opponent in an assigned mission area.

The specific areas of the game board that a player may be assigned an objective are left, right, crossover and overall. The following is a complete list of the mission areas a player may be assigned and a brief description of how each is achieved.

1. VL = Victory left. By scoring the most TTTs on the left side.
2. VR = Victory right. By scoring the most TTTs on the right side.
3. VC = Victory crossover. By scoring the most TTTs in the crossover area.
4. VO = Victory overall. By scoring the most total TTTs.
5. SL = Survival left. By not losing the left side.
6. SR = Survival right. By not losing the right side.
7. SC = Survival crossover. By not losing the crossover area.
8. SO = Survival overall. By not losing overall.

Each player can be assigned up to four missions. Like intelligence delays, different players can be assigned different missions. It should be evident at this time that there are numerous game configurations to choose from in Double Game Board T4.

4. Team T4 Games

Team T4 is a natural progression of the double game board version and introduces additional players, a controller and three types of intelligence delay.

a. Players

Team T4 is made up of two teams each with two players. The X team consists of an X Left (XL) player and an X Right (XR) player. Similarly, the O team is made up of an O Left (OL) player and an O Right (OR) player. Mission assignments are always the same for both players on the same team but opposing teams may be assigned different missions. This game is played like the other versions but tends to get complicated because of the increased number of delay factors which will be discussed below. To deal with the increased complexity of the game, a controller is assigned to monitor its progress.

b. Controllers

A controller administers the game, ensuring conflicts are resolved fairly and player's game boards are adjusted correctly taking into account the various delay factors. Like the other T4 versions players choose their moves in secrecy but instead of announcing them to their opponent, they give them to the controller. The controller then updates each individual game board and returns it to the player. The controller also maintains a master game board that represents ground truth, the actual status of the game without any intelligence delays. The intelligence delays that have been introduced into this version will now be presented.

c. Delay Factors

Intelligence delay has been expanded into three categories and they are described below.

1. Tactical delay. This delay refers to knowledge of own enemy move information (the opponent on the same side of the double game board).

2. Area delay. This delay refers to partner's enemy move information.

3. Communication delay. This delay refers to partner's move information.

These delays put constraints on the timeliness of receiving move information, by any one player, from the other three players. Each of the four players can be assigned different values for each of the three different delay types. These values, like the original intelligence delay, can vary from zero to nine moves.

d. Summary

At this point, the reader should feel reasonably comfortable that they have an understanding of the Team T4 game. To reinforce what has been discussed thus far, a quick review of the different factors that can be assigned to Team T4 games and the different levels some of these factors can take are summarized.

Two players each are assigned to the X and the O team. The teams are divided into left and right side players. Each team is assigned up to four mission areas with an objective of either victory or survival in each area. Recall that both sides on the same team are given the same mission assignment while the opposing team may have an entirely different assignment. Recall also that three types of delays can be assigned to each player, each varying from zero to nine moves. These delays can be different for each of the four players.

Experience has shown that while game play is fairly simple, the administration of the game is difficult, time consuming and susceptible to errors.

5. Auto T4

As might be expected, a computer assisted automation of the game was developed to assist the controller. This program is called Auto T4.

> This program allows pretrial configuration of the T4 games, computer assisted administration of game play and automatic scoring and collection of data. It is hoped that use of this aide by lead groups in 1991 T4 experiments will permit an increase in sample size and a reduction in data errors. [Ref. 3:p. 1]

It is important to realize that other than what is described directly above, there is no difference between Auto and Team T4.

6. T4 Simulation

A natural progression from the Auto T4 game is the T4 Simulation program. It simulates four players participating in Team T4 games, complete with mission assignments and intelligence delay constraints. Since Auto T4 already contained the software to score the game, to collect all the data generated by the simulation and to record it in a data file, the T4 Simulation program was produced by the addition of two major changes.

The first addition was a method to control the simulated play of each player. The problem with simulating human play was creating the software to do it. To accomplish this, each simulated player is controlled by a set of three game plan matrices.

The second addition allowed multiple trial runs to be accomplished without user intervention between trials and between configurations. A game file, that contains all configuration information, allows the user to specify multiple trial configurations and the number of replications to be run for each configuration.

The original purpose of the T4 simulation was to act as a surrogate for human play in a pilot experiment to discover a set of T4 variables of interest for later use in trials with human subjects. It was thought that this would be beneficial in several ways. Using simulated trials is extremely cost effective in terms of time required.

> Simulation permits the use of a much larger sample size resulting in a higher degree of resolution of results inferred from data. Use of simulated players thus adds greatly to the degree of control and independence of the trial outcomes. Humans make mistakes, learn from experience, play differently with different partners and other sometimes unknown factors that serve to add noise to the data in which you are trying to find a signal. [Ref. 4:p. 1]

This chapter introduced the T4 game to the reader. The purpose of the thesis was discussed including the research questions and the approach taken to answer them. The following chapter will describe the experimental design that was used to generate the data.

II. EXPERIMENTAL DESIGN

A. SETUP

In presenting the setup of an experimental design, the physical setup, the test subjects and any special equipment should be described. This is fairly simple when a simulation is used to generate the data. When using a simulation, all that is required is a computer and the necessary software. While using human subjects in the experiment, other issues such as assignment of teams and controllers, scheduling of when and where game play will be conducted, keeping score and data collection must be addressed. For completeness though, the hardware and software used to run the simulation and to collect and analyze the generated data will be described.

1. Physical

Gary Porter's T4 Simulation was run on a Macintosh microcomputer in Hypercard 2.0. T4 is written in Hypercard. It contains the code which simulates game play and then sends the generated data to a data file. The data is copied to disc in text format and then imported into Minitab or Microsoft Excel, the two software packages used to analyze and graph the data. Minitab was used as a statistical tool to do the majority of the analysis while Microsoft Excel was used to manipulate the data and produce the graphs shown in chapter three.

2. T4 Simulation

Before discussing the simulation setup, it is important to realize that this thesis does not fully utilize the full potential of the T4 Simulation in generating different configurations. As the simulation setup is described, it will be pointed out where the full range of possible parameters was not used.

The setup of the T4 Simulation requires the assignment of the following parameters. They need not be assigned in the order listed below, but they all must be assigned before the simulation can run.

1. player intelligence delay levels (Area, Communication and Tactical) from zero to nine turns,
2. three player strategy matrices which control simulated player game play,
3. team missions (up to four survival or victory mission areas),
4. the number of replications per configuration, and
5. methods for resolving same turn conflicts.

The first research question attempts to answer a question asked by Richardson in his thesis. Therefore, his T4 Simulation setup, except for increased sample size, will be used to generate data to answer Question 1 and is presented below. To answer research questions two through four, some changes to Richardson's setup were required. Changes to his setup are clearly identified as they are discussed.

a. Intelligence Delays

Team X was chosen as the control team, the team with zero information delay throughout the experiment. The O team then, received information delays during the experiment and as such, was considered the treatment team. During the experiment, both simulated O team players, left and right side, always received the same level of information delay. Each of the three types of delay were investigated separately. For example, when Area Delay was increased from zero to nine, the delay levels for Communication and Tactical Delay were held constant at zero. All nine levels of delay were investigated.

When data was generated to answer questions two through four, only Tactical Delay was considered, the other two types of delay (Area and Communications) were not. For Tactical Delay, only levels zero through three were investigated. The reasons for this will be discussed in the next chapter. Therefore, the full range of available parameters was not utilized while generating data for these questions.

b. Simulated Player Strategies

After determining the control and treatment team, strategies were assigned to control the simulated play of each player. Discussed briefly in the first chapter, strategy is controlled by a set of three game plan matrices. These game plan matrices include:

1. The Cell Game Plan matrix which determines where a player will move at the start of a game. It also assists in resolving same turn conflicts.

2. The Regular Game Plan matrix which controls a players moves on the left and right game boards.

3. The Crossover Game Plan matrix which controls a players move in the crossover area of the game board.

The game plan matrices are assigned point values by the user and the simulation uses these values to determine how the simulated players move. The way the players move represents their strategy. For an in depth discussion on how game plan matrices control simulated players, see Ref. 4.

Representative categories of available strategies, based on the values assigned to the game plan matrices, that can be assigned to each individual player are listed below:

1. Overall Offense: Ensures the simulated player will attempt to maximize own TTTs while making no attempt to block opponents TTTs.

2. Balanced Offense: Ensures the simulated player will primarily attempt to score own TTTs, but will also try to block opponent's. If there is simultaneously a TTT possible for the player and the opponent, a tie, the player will make an offensive TTT instead of blocking the opponent's TTT.

3. Balanced: This is the same as Balanced Offense except in the case of a tie. When a tie occurs, the choice of either making a TTT or blocking one is random.

4. Balanced Defense: Ensures the simulated player will primarily attempt to block opponent's TTTs, but will also try to score their own. If a tie occurs, the player will block the opponent's TTT rather than make one.

5. Total Defense: Ensures the simulated player will attempt to block opponent's TTTs while making no effort to score their own TTTs.

6. Random: This strategy provides the player with no strategy, all moves are random.

The strategies that were assigned for this experiment were offensive crossover, OC, for both left side players and defensive crossover, DC, for both right side players. OC, a variant of the Balanced Offense strategy, encourages the left side players to score TTTs in both the left and crossover areas of the double game board. DC, a variant of the Balanced Defense strategy, encourages the right side players to block their opponent's TTTs at the expense of scoring their own in the right and crossover areas. These simulated player strategies are realized as a result of assigning different values to the game plan matrices. It should be noted that each player can be assigned one strategy.

c. Mission Assignments

The mission assignments were VL and VC for both teams. Because both teams were assigned identical missions the possibility of same turn conflicts was maximized. It was expected that this setup would be best for determining what happens when changing the P(W) is investigated. Recall the full range of possible mission assignments includes eight different missions, see p.9. The simulation allows each team to be assigned up to four missions. Once again the full range of available parameters was not utilized.

d. Replications

The number of replications per configuration was increased from 30 to 120 to generate data to answer all of the research questions. It was believed that a sample size this large would result in a higher degree of resolution of the results inferred from the data. The only limit to the number of replications is the number of rows available on the spreadsheet used to analyze the data

e. Same Turn Conflict Resolution

Finally, same turn conflict resolution was random for all conflicts, initial and subsequent. To answer the research questions two through four, the O team was assigned a different P(W) for each game configuration ranging from 1.0 to 0.0 in steps of 0.1. For example, the O team for the first 120 replications was assigned P(W) = 1.0. The X team then, was automatically assigned the complementary value of P(W) = 0.0. This probability applied to both initial and subsequent same turn conflicts. The T4 Simulation program user can assign a P(W) from 1.0 to 0.0 for the first conflict that occurs. All subsequent conflicts can be resolved either randomly or alternately. Different P(W)s may be assigned for initial and subsequent same turn conflicts.

The purpose for pointing out the full range of T4 configuration options is not to critique the thesis but to point out that many more configurations are available for additional study.

B. PROCEDURE

After the generated data was transferred to disc it was reduced and manipulated in Microsoft Excel and put into columns for analysis. Both the statistical package in Excel and Minitab require data to be in columns for subsequent analysis. The raw data extracted from the original spreadsheet consisted of eight columns. Four each for the X and O teams. Each four column group was labeled *Scoring by TTTs* and the individual columns were labeled as follows:

1. *TL* which represents the total TTTs achieved on the left side game board.

2. *TC* which represents the total TTTs achieved on the crossover area of the game board.

3. *TR* which represents the total TTTs achieved on the right side game board.

4. *TO* which represents the total TTTs achieved on the entire game board is the sum of the first three columns.

Since the assigned missions did not include VR, the *TR* values were eliminated and *TO* was recalculated using only the *TL* and *TC* columns. The margin of victory, MOV, was then established using the following equation: $MOV = TO_x - TO_o$. In other words, the MOV is the difference between the total X team TTTs and the total O team TTTs in the assigned mission areas. It is the MOV columns that are statistically analyzed in this thesis and no further data manipulation was required.

The following chapter discusses the statistical methods used to analyze the MOV and presents the results of the analysis.

III. ANALYSIS

A. ANALYSIS PLAN

The plan used to generate and analyze the data that answered the first research question was produced by Richardson for his thesis. Recall that the Measure of Effectiveness (MOE), referred to earlier as the MOV, he selected was the difference in total TTTs between the X and O sides in the assigned mission areas. The mission areas selected for both teams were VL and VC. Conflict resolution for same turn conflicts was random, P(W) = 0.5, for both initial and subsequent conflicts. The player strategies assigned as diescribed in chapter two were OC for both left side players and DC for both right side players. Recall also that Area, Communication and Tactical delays between zero and nine turns were applied to the O side only. Thirty replications were run for each configuration totaling 10*3*30 = 900 trials.

After question one was answered, it was determined that Area and Communication Delays at any level and delay levels above one for Tactical Delay were not statistically significant. Therefore they were not considered while generating data to answer the final two questions. Unlike the plan that was used to answer the first research question, same turn conflicts were no longer resolved randomly with P(W) = 0.5. A change in the T4 software enables the user to select the P(W) for the O team on each side of the game board. Four inputs are available. The user can assign a P(W) for the initial same turn conflict for the left side O player and a P(W) for subsequent same turn conflicts for the same player. The same options are available for the right side O player. The T4 software assigns the complementary P(W) to the X player automatically. In this analysis, P(W) was set the same for each player on a team for both initial and subsequent same turn conflicts. P(W) ranged from 1.0 to 0.0 in increments of 0.1 for a total of eleven categories. The T4 simulation was run at these assigned P(W)s for each delay level (0, 1, 2 and 3) for 120 replications per configuration resulting in a total of 11*4*120 = 5280 trials.

B. METHODOLOGY

This section will discuss the statistical methods used to analyze the generated data. Not all the methods below were used to answer each question. The methods used will be referred to in the results.

1. Distribution

The techniques used to analyze the data required an assumption if they were to be valid: The population from which the sample is drawn must closely resemble a normal distribution. The first requirement then was to prove that the data was at least approximately normal.

According to the Central Limit Theorem (C.L.T.), given a random sample from a distribution with mean μ and variance σ^2, if the sample size is sufficiently large, the sample mean has approximately a normal distribution. A rule of thumb for sufficiently large is a sample size greater than 30.

Rather than just assume normality based on the C.L.T., two simple graphical techniques were used to support this assumption. The first technique was the histogram. The histogram provides a pictorial representation of the frequency distribution. If the data is normal, the tops of the columns generated by the histogram can be connected with a smooth line and the resulting curve will look similar to the standard normal curve. The second technique was the normal probability plot, which was generated to supplement the histogram in checking for normality. A normal probability plot that is close to a straight line suggests that the assumption of a normal distribution is plausible. When these techniques show that the data is normal, the following tools can be used for the data analysis.

2. Single-Factor Analysis of Variance

Analysis of variance, ANOVA, is a statistical tool that can be used to study the relation between a dependent variable, average MOV in this case, and one or more independent variables. The independent variables are called factors and are represented by different types of delay and P(W) in this thesis. Single-Factor ANOVA investigates one factor at a time while the other factor is held constant to see if the factor being investigated has any effect on the dependent variable. The question of central interest using ANOVA is whether there are differences in the sample means (μ_i's) associated with different combinations of delay and P(W). The sample mean being referred to is the mean MOV. ANOVA determines whether the average MOV for a particular level of delay, a, is statistically different than the average MOV for some other delay level, a_o, while holding P(W) constant. ANOVA will investigate all possible pairs of delay, a_0 =

a_1, $a_0 = a_2$, ... etc., and determine if the average MOV between different pairs of a are the same or different. To answer this question the following null and alternative hypotheses are tested.

1. H_o: $\mu_1 = \mu_2 = \cdots = \mu_9$,
2. H_a: at least two of the μ_i's are different.

If H_o is accepted, it can be concluded that delay has no effect on average MOV. If H_a is accepted, then average MOV differs among different levels of delay.

The method used for choosing between H_o and H_a is evaluation of the F statistic. In general, large values of F support H_a while values near one support H_o. Both Minitab and Microsoft Excel generate the F test statistic. To determine precisely which alternative should be chosen, the F test statistic is compared with the F critical value. The F critical value is generated by Excel but Minitab users must look it up in tables of F critical values which are available in any statistics text. If the F test statistic is less than the F critical value, H_o is accepted. Conversely, if the test statistic is greater than the critical value, H_a is accepted. It should be pointed out that the F critical value depends on the assigned value of the significance level α. As the value of α decreases, the F critical value increases. For example, if H_o is just barely rejected at $\alpha = 0.05$, it is possible that at $\alpha = 0.01$ the F critical value would become larger than the F test statistic and H_o could be accepted.

3. Two-Factor ANOVA

Since single-factor ANOVA investigates the effect of one factor at a time while holding other factors constant, it has some limitations. To investigate the effects of both factors, delay and P(W) simultaneously, a stronger analysis tool is required. Two-factor ANOVA provides this capability along with some important advantages over single-factor ANOVA.

Two-factor ANOVA is more efficient than its single-factor counterpart. Single-factor ANOVA provides no information about the factor being held constant. As a result, numerous single-factor runs had to be run in order to investigate all possible P(W) and delay combinations. Two-factor ANOVA allows all data to be stored in a matrix and analyzed in a single run.

The single-factor study also provides less information than the two-factor study. Although numerous single-factor runs were generated, no information about any special joint effects between delay and P(W) were provided. These joint effects are called interactions and indicate that the effects of each factor should not be discussed separately. When interactions exist, it must be determined if they are important.

> The determination of whether interactions are important or unimportant is admittedly sometimes difficult. This decision is not a statistical decision and should be made by the subject area specialist (researcher). The advantage of unimportant (or no) interactions, namely, that one is then able to analyze the factor effects separately, is especially great when the study contains more than two factors.[Ref. 5:p. 687]

Like single-factor ANOVA, two-factor ANOVA also has null and alternate hypotheses. However, they are not as simple as single-factor hypotheses and a discussion of the parameters used in them is necessary before they are stated. In two-factor ANOVA, values known as interaction parameters and main effects are what is compared. Let:

1. $\mu = 1/IJ \; \Sigma_i \Sigma_j \mu_{ij}$,
2. $\mu_{i.} = 1/J \; \Sigma_j \mu_{ij}$, and
3. $\mu_{.j} = 1/I \; \Sigma_i \; \mu_{ij}$.

Where I and J represent the different levels of factor A and B. Factor A is Tactical Delay and has I=4 levels, while factor B is P(W) and has J= 11 levels. The data matrix then is I columns by J rows with each cell containing 120 MOVs, the number of replications for each Tactical Delay-P(W) combination. Thus μ is the true grand mean, $\mu_{i.}$ is the expected response averaged over all levels of one factor while the other factor is held constant, and the same is true for $\mu_{.j}$. Therefore, $\mu_{i.}$ is the mean of a column of data representing a constant time delay over all values of P(W).

Now define:

1. $\alpha_i = \mu_{i.} - \mu$ = the effect of factor A at level *i*,
2. $\beta_j = \mu_{.j} - \mu$ = the effect of factor B at level *j*, and
3. $\gamma_{ij} = \mu_{ij} - (\mu + \alpha_i + \beta_j)$ = the interaction parameter at level *ij*.

There are now three sets of hypotheses that will be considered:

1. H_{oAB}: $\gamma_{ij} = 0$ for all ij versus H_{aAB}: at least one $\gamma_{ij} \neq 0$
2. H_{oA}: $\alpha_1 = \cdots = \alpha_4 = 0$ versus H_{aA}: at least one $\alpha_i \neq 0$

3. H_{oB}: $\beta_1 = \cdots = \beta_{11} = 0$ versus H_{aB}: at least one $\beta_j \neq 0$

The interaction hypothesis, H_{oAB}, is tested first to determine if interactions exist. This hypothesis addresses Question 4. If H_{oAB}, is rejected and the interactions are determined to be important, straightforward interpretation of the results is not possible. However, if the interactions exist and are deemed unimportant, the two factors can be analyzed separately.

4. Tukey's Procedure

If H_o is rejected using single-factor ANOVA, it is important to know which μ_i's are significantly different from one another. Determining which μ_i's are different will show how the different factor levels effect mission outcome. To conduct this further analysis, a multiple comparison procedure will be used. There are a number of these procedures in statistics literature. The one that will be used in this thesis is called Tukey's Procedure. This procedure produces a collection of simultaneous confidence intervals about the true values of all pairwise differences between every sample mean. If an interval does not contain zero it can be concluded that the two means being compared differ significantly at level α.

5. Simple Linear Regression and Correlation

The objective of regression analysis is to exploit the relationship between two (or more) variables so that we can gain information about one of them through knowing values of the other(s) [Ref. 6:p. 453]. Minitab uses the least squares estimate method to generate a fitted regression line. The slope of the regression line provides insight into the relationship of the independent variable to the dependent variable, the average MOV. If the slope is zero, the line is horizontal and the average MOV is constant and does not depend on the independent variable, delay.

The sample correlation coefficient measures how strong the association is between two variables in a sample. It is always between -1 and +1. A positive correlation occurs when the MOV tends to increase as delay increases. A negative correlation implies the opposite. If there is almost no association between the two variables, then the sample correlation coefficient will be near zero.

The methods above were used to make the final conclusions about whether to accept or reject the null hypotheses. However, it is always wise to graph data prior to applying more sophisticated analysis techniques. Graphing data provides a preliminary idea of what to expect from the analysis. Graphs, when compared to the results of statistical methods, provide a visual description of what the results mean. Finally, graphical representation of data provides confirmation of results that may not be understood otherwise and should always be produced. In the following section, graphs will be used in support of results wherever applicable.

C. RESULTS

1. Time Delay

Research question one asked if there was a value of delay above which mission outcome for the O Team ceased to decline. It was expected that at an increased number of simulation replications, the data would smooth, clearly indicating the delay level above which mission accomplishment no longer declined. The results of single factor ANOVA will either prove or disprove this expectation, but before considering these results a look at the data graphically will provide a gut feeling for what to expect from the analysis.

a. Graphical Analysis

Figure 1 is a graph of the average MOV for each of the three types of delay plotted at a constant P(W) = 0.5. This graph shows by how much on average the X side beats the O side as intelligence delay applied to team O increases for each of the three types of delay. The graph indicates a clear increase in average MOV between delay levels zero and one for Tactical Delay, indicating an increase in mission outcome for the team. It is difficult to determine graphically though, if there is any significant change in the average MOV among Tactical Delays beyond one. The graphs of Area and Communication Delay do not indicate any significant relationships are present.

b. Normality Checks

To answer the first research question, single-factor ANOVA was used. Before conducting ANOVA, the data was checked for normality. The histograms generated for question one data produced columns similar to the standard normal curve and the normal probability plots generated fairly straight lines. An example of each is in Appendix A. Given the large sample size and the positive results of the graphical techniques, the assumption that the data was normal appears valid.

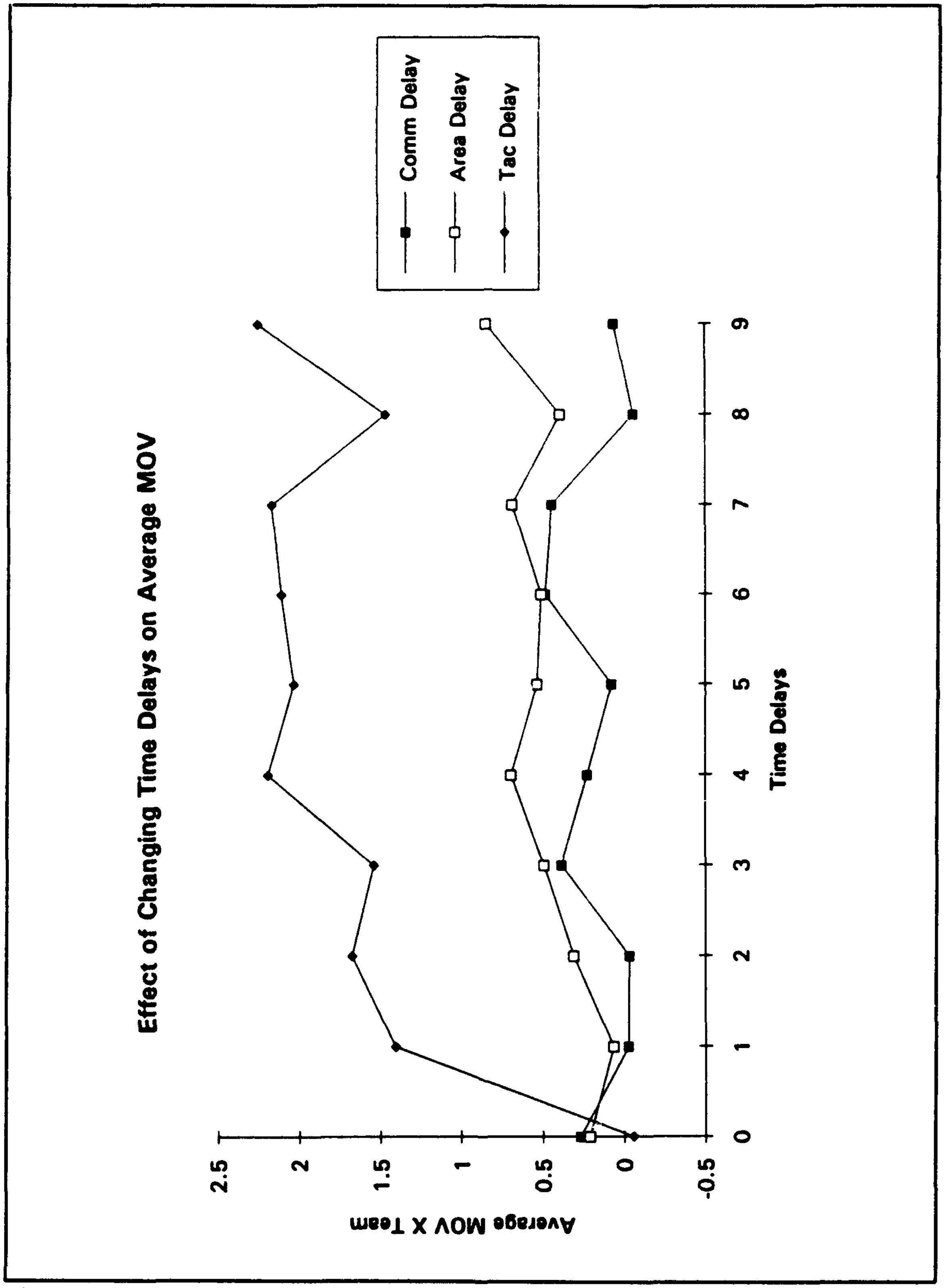

Figure 1. Average MOV vs. Time Delay

c. Single-Factor ANOVA

Appendix B has the results of the single-factor ANOVA conducted on each set of data. In the appendix *Groups* equate to time delays applied to team O. Comparison of the *F* test statistic against the *F* critical value reveals the null hypotheses for Area and Communication delays were accepted indicating no statistical difference between average MOVs at any level of delay. Comparison of the *F* values for Tactical Delay indicates rejection of H_o, thus requiring further analysis of the data to determine at which level(s) of Tactical Delay average MOVs differed.

Before discussing any further analysis, a more thorough discussion of some of the ANOVA table is presented.

The *Summary* section of the output consists of five columns and ten rows. The first column, *Groups*, represents each level of delay, Tactical Delays zero through nine and the *Count* column indicates the number of replications of each level. The total number of X team TTTs minus O team TTTs per replication, summed over all replications is in the *Sum* column while that same number divided by the count is stored in the *Average* column. This column is the average MOV. Finally, the *Variance* column contains the sample variance, s^2, about the average. Along with the assumption that the data is normal, an additional underlying assumption made in order to use ANOVA is that the different levels of delay have the same population variance, σ^2. Since σ^2 is usually not known, s^2 is used. The results show that the differences between them are negligible. However, if the assumptions about normality or variance seem doubtful, a knowledgeable statistician should be consulted.

The section labeled *ANOVA* contains the values that determine which hypothesis is accepted. The first value in this column represents the mean square for treatments, MSTr. As the average MOVs become more discrepant, this value increases indicating H_a is probably true. If σ^2 were available it could be compared directly to MSTr. If MSTr was considerably larger than σ^2, H_0 would be rejected. The second value in this column represents the mean square error, MSE. This value is an unbiased estimator of σ^2 and is the weighted average of the sample variances in the above section. The F test statistic is the result of dividing MSTr by MSE.

The next section in the ANOVA table to be discussed is the column labeled *SS*, sum of squares. The first value in this column is the treatment sum of squares, SSTr, the second value is the error sum of squares, SSE, and the third value is the sum of the first two and is appropriately named the total sum of squares, SST. The SST is a measure of the total variation in the data. The SSE measures the variation *within* the different levels of delay and is the unexplained part of the SST. SSTr measures the variation *between* the different delay levels, and is the explained part of the SST. Like the MS values, the ratio of the SS values, if each is divided by the correct degrees of freedom, df, can determine the F test statistic.

d. Tukey's Method

Tukey's method was used to generate a collection of confidence intervals about the true value of all pairwise differences between average MOVs for Tactical Delay, see Appendix C. It is up to the researcher to investigate the intervals and identify those that do not contain zero. In the appendix, row and column labels represent delay levels. The results show that Tactical Delay of zero, when compared with every other level of delay, was significantly different than all other levels. For example, the interval comparing delay levels zero and one ranges from -2.839 to -0.095 and does not include zero. Tukey's analysis indicates there is no significant difference in average MOV past a delay of one turn. Tukey's method by itself seemed to answer research question one. However, the graph of average MOV vs Time Delay, Figure 1, appears to indicate large differences between average MOVs beyond one for Tactical Delay. A straighter, more horizontal curve was expected if there were no significant differences between the average MOVs at delay levels one through nine. To confirm Tukey's results and to discount the visual analysis, a fitted regression line was plotted over the delay levels of interest to analyze the association between MOVs at these delay levels. The correlation coefficient, r, was also computed.

e. Corroboration of Tukey's Method

Simple linear regression was used to generate a regression equation, see Appendix D, to analyze the average MOV beyond Tactical Delay of one. The equation that is generated represents a line that is very nearly horizontal, slope = 0.065, indicating the MOV does in fact remain fairly constant after a delay level of one. Along with the results of linear regression, a correlation coefficient was generated. The coefficient is close to zero, $r = 0.04$, indicating there is almost no association between Tactical Delay and average MOV. This corroborates the Tukey results, i.e., the only difference between average MOV is the difference that exists between Tactical Delay levels zero and one.

2. Changing P(W)

The response to question one, showed that only Tactical Delay effected average MOV. Further, using Tukey's method it was further determined that significant differences in average MOV only occurred between Tactical Delay levels zero and one. It was expected that the results from Question 1 analysis would allow elimination of insignificant delay levels. Analysis showed that significant changes ceased to exist beyond a delay of one. The remainder of the research questions introduce an additional factor, P(W). There was uncertainty regarding whether including P(W) would change the results beyond a delay of one. To protect against this outcome Tactical Delay levels from zero to three were used for the remainder of the analysis. The second research question investigates the relationship between MOV and P(W) as P(W) varies from 1.0 to 0.0 in increments of 0.1 while the levels of Tactical Delay vary from zero to three.

a. Normality Checks

This configuration was also analyzed using single-factor ANOVA. The data was checked for normality and the results of histograms and normal probability plots confirmed it. Single-factor ANOVA was run at each level of Tactical Delay to determine the effect of changing P(W)s on average MOV at constant levels of Tactical Delay.

b. Graphical Analysis

The graphical analysis is based on Figure 2 which shows that a steady increase in MOV for the X team occurs as the P(W) for the O team decreases. It also

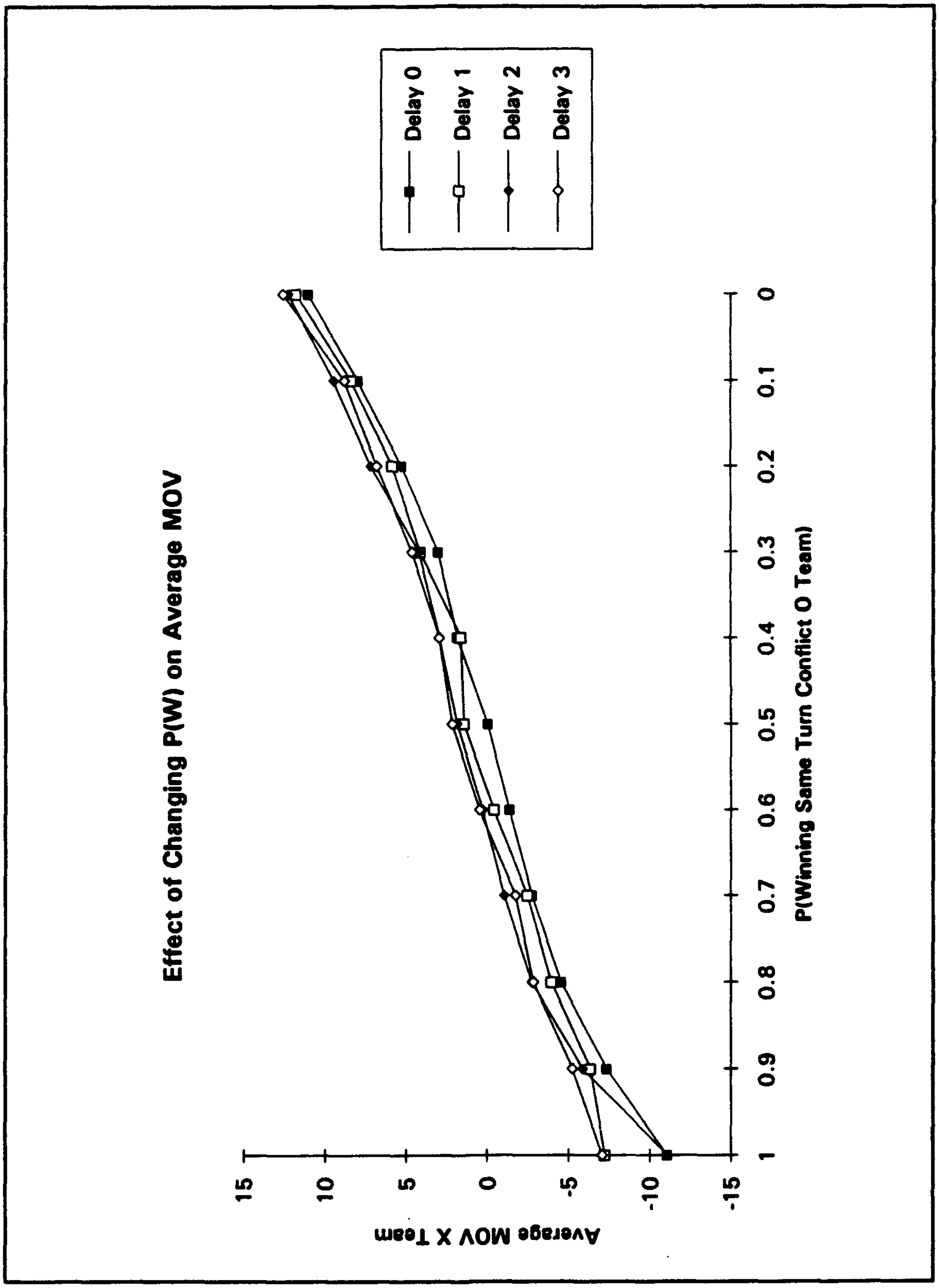

Figure 2. Average MOV vs. P(W)

appears that increasing delay level for team O results in a higher MOV for team X, although the differences appear slight and are probably insignificant.

c. *Single-Factor ANOVA*

Based on ANOVA the null hypothesis was rejected all four times indicating that P(W) significantly effects average MOV at all four levels of delay. To determine which different levels of P(W) effect the average MOV, Tukey's method was used once again.

d. *Tukey's Method*

Tukey's method generated confidence intervals revealing how pairwise levels of P(W) effected average MOVs. The results are in Appendix F. These results indicate that the majority of the pairwise comparisons have a significantly different effect on average MOV. At Tactical Delay zero for example, just three pairs of P(W) have the same effect on average MOV at $\alpha = 0.05$. The interval comparing P(W) = 0.6 and P(W) = 0.5 contains zero, indicating the average MOV does not differ significantly between those two P(W)s. It can be stated then that at Tactical Delay 0, no significant increase in average MOV would exist between P(W) = 0.5 and P(W) = 0.6. The same can be said for all intervals that do not contain zero.

e. *Linear Regression*

Simple linear regression was used once again to determine regression equations for the data at each level of delay. See Figure 3. The slopes of these equations indicate by how much an increase of 0.1 in P(W) contributes to an increase in the average MOV for the X team. Based on these equations, it appears that a 0.1 increase in P(W) increases the average MOV by approximately 2.0 TTTs.

The *R-sq* (r-squared) value, which is the correlation coefficient squared is shown in Appendix G contains along with the regression equations. For example, at Tactical Delay 0, *R-sq* = 75.2% indicating the regression equation for that delay explains 75.2% of the variation in the average MOV. The average R-sq value for all four delay levels is 68.35%. From these results, it appears P(W) positively influences the average MOV. Thus, both of the second research questions and the third as well have been answered.

3. Interactions

Finally, the fourth research question asks if an interaction exists between Tactical Delay and P(W). To determine if interactions exist, two-factor ANOVA was used. The same data used in Question 2 was used again so the requirement that the data be normal has already been confirmed. The data were manipulated into a single I by J matrix to enable the software to analyze it. ANOVA was then run on the data and the results are in Appendix H. The area of interest in the ANOVA results is the row labeled *interaction*. Notice the F test statistic there is greater than the F critical value, implying that H_{oAB} is rejected and interactions between delay and P(W) do exist. In following the methodology used in the previous two questions, the data was graphed and then compared with the results provided by ANOVA.

a. Graphical Results

Figure 2 is also a graph of the interactions. If no interactions existed, the four curves would be parallel and wouldn't intersect. Since they do intersect and the results of ANOVA show that interactions exist, it is up to the researcher to determine if the interactions are important. If they are not, the factors can be analyzed separately and the results of Question 2 are all that need to be considered when analyzing this set of data.

To determine if interactions are important it is necessary to see how strong the interactions are. Figure 2 shows that all four curves plot similarly and generally have about the same slope. The graph reveals overall a delay level of three results in a larger average MOV than a delay of two. The same is true when two is compared to one and one to zero. Closer investigation of Figure 2 indicates that eight times out of eleven, the average MOV is greatest for delay level three and decreases in order down to level zero.

b. Regression Analysis

To investigate the graph further, the regression equations generated earlier were once again investigated, see Figure 3 or Appendix G. Comparison of the slopes will indicate how away from parallel the four curves are. The slopes and y-intercepts for all four curves are very similar indicating the best fit curves are very close to parallel.

$$\text{Average } MOV_0 = -11.6 + 1.96P(W)$$
$$\text{Average } MOV_1 = -9.69 + 1.81P(W)$$
$$\text{Average } MOV_2 = -10.5 + 2.01P(W)$$
$$\text{Average } MOV_3 = -8.89 + 1.80P(W)$$
$$\text{Average } MOV = -11.6 + 1.90P(W) + 0.573\text{Delay}$$

Figure 3. Regression Equations

c. *Additional Analysis*

Recall the *R-sq* value shows the amount of variation between the data sets that can be explained by least squares regression. The results here are similar ranging from $\approx 55\%$ to $\approx 75\%$. Additionally, the F values were compared to see if H_{oAB} was rejected by a large amount. The F test statistic is relatively close to the F critical value indicating H_{oAB} was not strongly rejected.

d. *Conclusions*

Based on Figure 2, the regression equations, the similarity between correlation coefficients and the small margin between the F test statistic and the F critical value, it is the opinion of the author that, although interactions exist between Tactical Delay and P(W), they are unimportant and do not effect the average MOV.

e. *Multiple Regression*

Finally, a multiple linear regression was run on the data to analyze the combined influence of P(W) and Tactical Delay on average MOV over the entire I by J matrix. The regression equation, see the fourth equation in Figure 3 above, indicates that P(W) has more than three times the effect on average MOV than Tactical Delay. This further corroborates the the graphical analysis that shows the almost complete dominance of P(W) over delay.

This chapter discussed the methodology used to analyze the data and the results of the analysis. The final chapter of this thesis will include the conclusions, a summary of the experiment and some recommendations for further study in this area.

IV. CONCLUSIONS

The purpose of this thesis was to design, conduct, analyze and report the results of a C3 experiment. The T4 Simulation generated data for analysis so the research questions in the first chapter could be answered. The remainder of this chapter summarizes the thesis results presented earlier.

A. RESEARCH QUESTION RESULTS

The data generated and analysis conducted was sufficient to answer the stated research questions. The last chapter discussed the data analysis and provided conclusions to the research questions posed in the first chapter. Below the questions are answered directly, a brief summary of the experiment is provided and the thesis closes with recommendations for further studies in this area.

1. Delay Levels

It was determined that Tactical Delay of zero was significantly different than delays one through nine. Analysis of delays one through nine indicated no significant change in average MOV among those delays. Area and Communication Delays showed no significant difference in average MOV at any level. Therefore, based on the configuration of this experiment, it can be concluded that:

1. Only Tactical Delay significantly effects average MOV, and
2. There is a level of delay beyond which average MOV ceases to decline and it has been determined to be Tactical Delay = 1.

2. P(W)

This section will answer research questions 2a, 2b and 3. In all cases, changing the level of P(W) provides a distinct increase in average MOV for the team assigned the greater value of P(W). The average MOV increases linearly with an increase in P(W) and at no level does a further increase in P(W) not result in an increase in average MOV. It was determined that an increase of 0.1 in P(W) results in an increase of approximately two TTTs. These results remained approximately the same regardless of the level of Tactical Delay.

3. Delay and P(W) Interactions

Finally, it was determined that an interaction existed between Tactical Delay and P(W). The interaction was determined to be unimportant and the two factors were analyzed separately. Separate analysis was accomplished using single-factor ANOVA previously and no further analysis was required.

B. SUMMARY

This experiment enabled the researcher to use several statistical tools to analyze data generated by the T4 Simulation. The simulation, acting as a surrogate for a C3 system, provides data which allows the researcher to determine an optimal combination of the assigned variables, i.e., an optimal *system alignment*. In this specific configuration the X team player assigned P(W) = 1.0 playing against an O team assigned Tactical Delay one or greater will always be more successful than any other configuration.

This type of experiment lends itself well to systems evaluation. For example, if a C3 system were being analyzed to try and determine the optimal setting of system parameters, an analysis similar to this one could be conducted and an optimal *systems alignment* could be determined statistically.

C. RECOMMENDATIONS

The T4 Simulation is an excellent tool for generating C3 related data to determine an optimal T4 configuration. The number of configurations are numerous and the spreadsheet generated is full of data to be analyzed. The only recommendations this author can suggest is to take advantage of the different configurations available in the T4 simulation.

There are several options for a continuation to this thesis. Chapter two points out several parameters that were not investigated. Another researcher may attempt to replicate the above results using a completely different configuration. After the systems evaluation course, C3 students will be very familiar with this simulation and may want to propose a configuration that interests them, predict what they think will happen, and test their predictions using some or all of the tools presented in this thesis. There are vast opportunities for the C3 student who enjoys this type of analysis to pursue this area for thesis study.

APPENDIX A: CHECKING FOR NORMALITY

Histogram of Area Delay at level 0, N = 120

```
Midpoint  Count
   -8       1  *
   -6       0
   -4      11  ***********
   -2      25  *************************
    0      28  ****************************
    2      30  ******************************
    4      16  ****************
    6       7  *******
    8       2  **
```

Normal Probability Plot of Area Delay at level 0

```
      -                                     2
      -
  5.0+                                   7
      -                               8
      -                             8
      -                           +
      -                         +
  0.0+                          +
      -                      +
      -                    +
      -                 9
      -               6
 -5.0+              5
      -
      -
      -   *
      -
       +---------+---------+---------+---------+---------+------C4
     -3.0      -2.0      -1.0       0.0       1.0       2.0
```

Histogram of Communication Delay at level 0,   N = 120

```
Midpoint  Count
   -10      1 *
    -8      1 *
    -6      2 **
    -4      5 *****
    -2     28 ****************************
     0     28 ****************************
     2     30 ******************************
     4     15 ***************
     6      5 *****
     8      4 ****
    10      1 *
```

Normal Probability Plot of Communication Delay at level 0

```
     -
     -                                           *
     -                                         *
 7.0+                                         3
     -                                    4 *
     -                                  9
     -                                6
     -                           +   +
 0.0+                            +
     -                      +   +
     -                  8
     -
     -           * 5
-7.0+             *
     -         *
     -     *
     -
       ------+--------+--------+--------+--------+--------C5
          -2.0      -1.0      0.0      1.0      2.0
```

Histogram of Tactical Delay at level 0, N = 120

```
Midpoint  Count
   -8       1  *
   -6       2  **
   -4      14  **************
   -2      20  ********************
    0      30  ******************************
    2      33  *********************************
    4      14  **************
    6       4  ****
    8       2  **
```

Normal Probability Plot of Tactical Delay at level 0

```
      -                                             2
      -
  5.0+                                           4
      -                                       5
      -                                    9
      -                                  +
      -                              +
  0.0+                              +
      -                         +
      -                       +
      -                    5
      -                  +
 -5.0+               3
      -          *
      -        *
      -     *
      -
       +---------+---------+---------+---------+---------+------C6
     -3.0      -2.0      -1.0       0.0       1.0       2.0
```

APPENDIX B: SINGLE-FACTOR ANOVA

Anova:Single-Factor   Area Delay

Summary

Groups	Count	Sum	Average	Variance
0	120	25	0.208	8.318
1	120	8	0.067	6.802
2	120	37	0.308	8.148
3	120	59	0.492	8.336
4	120	83	0.692	7.022
5	120	64	0.533	5.965
6	120	61	0.508	5.798
7	120	82	0.683	6.336
8	120	47	0.392	6.660
9	120	101	0.842	8.118

ANOVA

Source of Variation	SS	df	MS	F	P-val	F crit
Between Groups	60.3	9	6.7	0.94	0.492	1.89
Within Groups	8508.8	1190	7.2			
Total	8569.1	1199				

Anova:Single-Factor   Comm Delay

Summary

Groups	Count	Sum	Average	Variance
0	120	32	0.27	10.6
1	120	-3	-0.025	7.991
2	120	-4	-0.033	7.427
3	120	46	0.383	8.205
4	120	27	0.225	6.058
5	120	9	0.075	7.818
6	120	58	0.483	6.806
7	120	53	0.442	7.912
8	120	-7	-0.058	7.114
9	120	7	0.058	7.770

ANOVA

Source of Variation

	SS	df	MS	F	P-val	F crit
Between Groups	45.8	9	5.1	0.655	0.75	1.89
Within Groups	9242.6	1190	7.77			
Total	9288.397	1199				

Anova: Single-Factor Tactical Delay

Summary

Groups	Count	Sum	Average	Variance
0	120	-7	-0.058	7.971
1	120	169	1.408	10.328
2	120	201	1.675	9.986
3	120	185	1.542	11.679
4	120	263	2.192	10.711
5	120	244	2.033	12.520
6	120	253	2.108	10.770
7	120	260	2.167	13.165
8	120	176	1.467	13.327
9	120	270	2.250	12.609

ANOVA

Source of Variation

	SS	df	MS	F	P-value	F crit
Between Groups	515.1	9	57.23	5.06	0	1.89
Within Groups	13454.8	1190	11.3			
Total	13969.84	1199				

APPENDIX C: TUKEY'S RESULTS

Tukey's Pairwise Comparisons
Family error rate = 0.0500
Individual error rate = 0.00160

Critical value = 4.47

Intervals for (column level mean) - (row level mean)

	0	1	2	3	4	5	6	7	8
1	-2.839 -0.095								
2	-3.105 -0.361	-1.639 1.105							
3	-2.972 -0.228	-1.505 1.239	-1.239 1.505						
4	-3.622 -0.878	-2.155 0.589	-1.889 0.855	-2.022 0.722					
5	-3.464 -0.720	-1.997 0.747	-1.730 1.014	-1.864 0.880	-1.214 1.530				
6	-3.539 -0.795	-2.072 0.672	-1.805 0.939	-1.939 0.805	-1.289 1.455	-1.447 1.297			
7	-3.597 -0.853	-2.130 0.614	-1.864 0.880	-1.997 0.747	-1.347 1.397	-1.505 1.239	-1.430 1.314		
8	-2.897 -0.153	-1.430 1.314	-1.164 1.580	-1.297 1.447	-0.647 2.097	-0.805 1.939	-0.730 2.014	-0.672 2.072	
9	-3.680 -0.936	-2.214 0.530	-1.947 0.797	-2.080 0.664	-1.430 1.314	-1.589 1.155	-1.514 1.230	-1.455 1.289	-2.155 0.589

APPENDIX D: LINEAR REGRESSION

The regression equation is

Average MOV = 1.55 + 0.0651 Tactical Delay

Predictor	Coef	Stdev	t-ratio	p
Constant	1.5456	0.2266	6.82	0.000
TacDel	0.06514	0.04027	1.62	0.106

s = 3.417 R-sq = 0.2% R-sq(adj) = 0.1%

APPENDIX E: SINGLE-FACTOR ANOVA

Changing P(W) at Time Delay 0
Anova: Single-Factor

Summary

Groups	Count	Sum	Average	Variance
1.0	120	-1326	-11.050	13.964
0.9	120	-885	-7.375	15.682
0.8	120	-550	-4.583	15.455
0.7	120	-334	-2.783	10.659
0.6	120	-166	-1.383	9.415
0.5	120	-7	-0.058	7.971
0.4	120	217	1.808	10.223
0.3	120	360	3.000	7.697
0.2	120	631	5.258	11.991
0.1	120	957	7.975	17.319
0.0	120	1322	11.017	13.126

ANOVA

Source of Variation	SS	df	MS	F	P-val	F crit
Between Groups	51809.87	10	5180.987	426.89	0	1.838
Within Groups	15886.79	1309	12.13659			
Total	67696.67	1399				

Changing P(W) at Time Delay 1
Anova: Single-Factor

Summary

Groups	Count	Sum	Average	Variance
1.0	120	-867	-7.225	36.361
0.9	120	-764	-6.367	25.125
0.8	120	-475	-3.958	21.250
0.7	120	-299	-2.492	15.865
0.6	120	-53	-0.442	12.249
0.5	120	169	1.408	10.328
0.4	120	188	1.567	12.735
0.3	120	496	4.133	13.696
0.2	120	702	5.850	15.154
0.1	120	1004	8.367	16.890
0.0	120	1412	11.767	12.332

ANOVA

Source of Variation	SS	df	MS	F	P-val	F crit
Between Groups	43746.7	10	4374.666	250.653	0	1.838
Within Groups	22846.1	1309	17.45311			
Total	66592.8	1319				

Changing P(W) at Time Delay 2
Anova: Single-Factor

Summary

Groups	Count	Sum	Average	Variance
1.0	120	-1332	-11.1	16.242
0.9	120	-709	-5.908	25.042
0.8	120	-332	-2.767	22.315
0.7	120	-127	-1.058	12.980
0.6	120	33	0.275	14.789
0.5	120	219	1.825	12.667
0.4	120	348	2.9	13.183
0.3	120	501	4.175	13.809
0.2	120	861	7.175	17.473
0.1	120	1137	9.475	18.336
0.0	120	1467	12.225	9.436

ANOVA

Source of Variation

	SS	df	MS	F	P-val	F crit
Between Groups	55188	10	5518.8	344.392	0	1.838
Within Groups	20976.4	1309	16.02475			
Total	76164.4	1319				

Changing P(W) at Time Delay 3
Anova: Single-Factor

Summary

Groups	Count	Sum	Average	Variance
1.0	120	-849	-7.075	32.272
0.9	120	-632	-5.267	30.584
0.8	120	-342	-2.85	21.624
0.7	120	-212	-1.767	16.668
0.6	120	55	0.458	15.948
0.5	120	257	2.142	10.744
0.4	120	350	2.917	13.859
0.3	120	556	4.633	16.217
0.2	120	813	6.775	17.588
0.1	120	1057	8.808	16.190
0.0	120	1505	12.542	9.746

ANOVA

Source of Variation

	SS	df	MS	F	P-val	F crit
Between Groups	43593.62	10	4359.4	238.052	0	1.838
Within Groups	23971.28	1309	18.3			
Total	67564.91	1319				

APPENDIX F: TUKEY'S RESULTS

Tukey's pairwise comparisons for **Tactical Delay= 0**

Family error rate = 0.0500
Individual error rate = 0.00132

Critical value = 4.55

Intervals for (column level mean) - (row level mean)

	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
0.9	-5.122 -2.228									
0.8	-7.914 -5.020	-4.239 -1.345								
0.7	-9.714 -6.820	-6.039 -3.145	-3.247 -0.353							
0.6	-11.114 -8.220	-7.439 -4.545	-4.647 -1.753	-2.847 0.047						
0.5	-12.439 -9.545	-8.764 -5.870	-5.972 -3.078	-4.172 -1.278	-2.772 0.122					
0.4	-14.305 -11.411	-10.630 -7.736	-7.839 -4.945	-6.039 -3.145	-4.639 -1.745	-3.314 -0.420				
0.3	-15.497 -12.603	-11.822 -8.928	-9.030 -6.136	-7.230 -4.336	-5.830 -2.936	-4.505 -1.611	-2.639 0.255			
0.2	-17.755 -14.861	-14.080 -11.186	-11.289 -8.395	-9.489 -6.595	-8.089 -5.195	-6.764 -3.870	-4.897 -2.003	-3.705 -0.811		
0.1	-20.472 -17.578	-16.797 -13.903	-14.005 -11.111	-12.205 -9.311	-10.805 - 7.911	-9.480 -6.586	-7.614 -4.720	-6.422 -3.528	-4.164 -1.270	
0.0	-23.514 -20.620	-19.839 -16.945	-17.047 -14.153	-15.247 -12.353	-13.847 -10.953	-12.522 -9.628	-10.655 -7.761	-9.464 -6.570	-7.205 -4.311	-4.489 -1.595

Tukey's pairwise comparisons for Tactical Delay = 1

Family error rate = 0.0500
Individual error rate = 0.00132

Critical value = 4.55

Intervals for (column level mean) - (row level mean)

	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
0.9	-2.594									
	0.877									
0.8	-5.002	-4.144								
	-1.531	-0.673								
0.7	-6.469	-5.610	-3.202							
	-2.998	-2.140	0.269							
0.6	-8.519	-7.660	-5.252	-3.785						
	-5.048	-4.190	-1.781	-0.315						
0.5	-10.369	-9.510	-7.102	-5.635	-3.585					
	-6.898	-6.040	-3.631	-2.165	-0.115					
0.4	-10.527	-9.669	-7.260	-5.794	-3.744	-1.894				
	-7.056	-6.198	-3.790	-2.323	-0.273	1.577				
0.3	-13.094	-12.235	-9.827	-8.360	-6.310	-4.460	-4.302			
	-9.623	-8.765	-6.356	-4.890	-2.840	-0.990	-0.831			
0.2	-14.810	-13.952	-11.544	-10.077	-8.027	-6.177	-6.019	-3.452		
	-11.340	-10.481	-8.073	-6.606	-4.556	-2.706	-2.548	0.019		
0.1	-17.327	-16.469	-14.060	-12.594	-10.544	-8.694	-8.535	-5.969	-4.252	
	-13.856	-12.998	-10.590	-9.123	-7.073	-5.223	-5.065	-2.498	-0.781	
0.0	-20.727	-19.869	-17.460	-15.994	-13.944	-12.094	-11.935	-9.369	-7.652	-5.135
	-17.256	-16.398	-13.990	-12.523	-10.473	-8.623	-8.465	-5.898	-4.181	-1.665

Tukey's pairwise comparisons for Tactical Delay = 2

Family error rate = 0.0500
Individual error rate = 0.00132

Critical value = 4.55

Intervals for (column level mean) - (row level mean)

	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
0.9	-6.854									
	-3.529									
0.8	-9.996	-4.804								
	-6.671	-1.479								
0.7	-11.704	-6.513	-3.371							
	-8.379	-3.187	-0.046							
0.6	-13.038	-7.846	-4.704	-2.996						
	-9.712	-4.521	-1.379	0.329						
0.5	-14.588	-9.396	-6.254	-4.546	-3.213					
	-11.262	-6.071	-2.929	-1.221	0.113					
0.4	-15.663	-10.471	-7.329	-5.621	-4.288	-2.738				
	-12.337	-7.146	-4.004	-2.296	-0.962	0.588				
0.3	-16.938	-11.746	-8.604	-6.896	-5.563	-4.013	-2.938			
	-13.612	-8.421	-5.279	-3.571	-2.237	-0.687	0.388			
0.2	-19.938	-14.746	-11.604	-9.896	-8.563	-7.013	-5.938	-4.663		
	-16.612	-11.421	-8.279	-6.571	-5.237	-3.687	-2.612	-1.337		
0.1	-22.238	-17.046	-13.904	-12.196	-10.863	-9.313	-8.238	-6.963	-3.963	
	-18.912	-13.721	-10.579	-8.871	-7.537	-5.987	-4.912	-3.673	-0.637	
0.0	-24.988	-19.796	-16.654	-14.946	-13.613	-12.063	-10.988	-9.713	-6.713	-4.413
	-21.662	-16.471	-13.329	-11.621	-10.287	-8.737	-7.662	-6.387	-3.387	-1.087

Tukey's pairwise comparisons for Tactical Delay = 3

Family error rate = 0.0500
Individual error rate = 0.00132

Critical value = 4.55

Intervals for (column level mean) - (row level mean)

	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
0.9	-3.586									
	-0.031									
0.8	-6.002	-4.194								
	-2.448	-0.639								
0.7	-7.086	-5.277	**-2.861**							
	-3.531	-1.723	**0.694**							
0.6	-9.311	-7.502	-5.086	-4.002						
	-5.756	-3.948	-1.531	-0.448						
0.5	-10.994	-9.186	-6.769	-5.686	**-3.461**					
	-7.439	-5.631	-3.214	-2.131	**0.094**					
0.4	-11.769	-9.961	-7.544	-6.461	-4.236	**-2.552**				
	-8.214	-6.406	-3.989	-2.906	-0.681	**1.002**				
0.3	-13.486	-11.677	-9.261	-8.177	-5.952	-4.269	**-3.494**			
	-9.931	-8.123	-5.706	-4.623	-2.398	-0.714	**0.061**			
0.2	-15.627	-13.819	-11.402	-10.319	-8.094	-6.411	-5.636	-3.919		
	-12.073	-10.264	-7.848	-6.764	-4.539	-2.856	-2.081	-0.364		
0.1	-17.661	-15.852	-13.436	-12.352	-10.127	-8.444	-7.669	-5.952	-3.811	
	-14.106	-12.298	-9.881	-8.798	-6.573	-4.889	-4.114	-2.398	-0.256	
0.0	-21.394	-19.586	-17.169	-16.086	-13.861	-12.177	-11.402	-9.686	-7.544	-5.511
	-17.839	-16.031	-13.614	-12.531	-10.306	-8.623	-7.848	-6.131	-3.989	-1.956

APPENDIX G: LINEAR REGRESSION

The regression equation at Tactical Delay 0 is
Average MOV = - 11.6 + 1.96 P(W)

Predictor	Coef	Stdev	t-ratio	p
Constant	-11.6168	0.2107	-55.13	0.000
C46	1.96379	0.03107	63.21	0.000

s = 3.569 R-sq = 75.2% R-sq(adj) = 75.2%

The regression equation at Tactical Delay 1 is
Average MOV= - 9.69 + 1.81 P(W)

Predictor	Coef	Stdev	t-ratio	p
Constant	-9.6852	0.2497	-38.79	0.000
C48	1.80523	0.03681	49.04	0.000

s = 4.229 R-sq = 64.6% R-sq(adj) = 64.6%

The regression equation at Tactical Delay 2 is
Average MOV = - 10.5 + 2.01P(W)

Predictor	Coef	Stdev	t-ratio	p
Constant	-10.4935	0.2458	-42.69	0.000
C50	2.00977	0.03624	55.46	0.000

s = 4.163 R-sq = 70.0% R-sq(adj) = 70.0%

The regression equation at Tactical Delay 3 is
Average MOV = - 8.89 + 1.80P(W)

Predictor	Coef	Stdev	t-ratio	p
Constant	-8.8903	0.2549	-34.88	0.000
C52	1.80470	0.03758	48.02	0.000

s = 4.318 R-sq = 63.6% R-sq(adj) = 63.6%

APPENDIX H: TWO-FACTOR ANOVA

Anova: Two-Factor With Replication

Summary

	Delay0	Delay 1	Delay 2	Delay 3	Total
P(W)=1.0					
Count	120	120	120	120	480
Sum	-1326	-867	-1332	-849	-4374
Average	-11.05	-7.23	-11.1	-7.075	-36.45
Variance	13.96	36.36	16.24	32.27	98.84
P(W)=0.9					
Count	120	120	120	120	480
Sum	-885	-764	-709	-632	-2990
Average	-7.375	-6.37	-5.91	-5.23	-24.92
Variance	15.68	25.12	25.04	30.58	96.43
P(W)=0.8					
Count	120	120	120	120	480
Sum	-550	-475	-332	-342	-1699
Average	-4.58	-3.96	-2.77	-2.85	-14.16
Variance	15.46	21.25	22.31	21.624	80.64
P(W)=0.7					
Count	120	120	120	120	480
Sum	-334	-299	-127	-212	-972
Average	-2.78	-2.49	-1.0[illegible]	-1.77	-8.1
Variance	10.66	15.87	12.98	16.67	56.17
P(W)=0.6					
Count	120	120	120	120	480
Sum	-166	-53	33	55	-131
Average	-1.38	-0.44	0.275	0.46	-1.09
Variance	9.41	12.25	14.79	15.95	52.40

P(W)=0.5

Count	120	120	120	120	480
Sum	-7	169	21.9	257	638
Average	-0.06	1.41	1.83	2.14	5.32
Variance	7.97	10.33	12.67	10.74	41.71

P(W)=0.4

Count	120	120	120	120	480
Sum	217	188	348	350	1103
Average	1.81	1.57	2.9	2.92	9.19
Variance	10.22	12.74	13.18	13.86	50.00

P(W)=0.3

Count	120	120	120	120	480
Sum	360	496	501	556	1913
Average	3	4.13	4.18	4.63	15.94
Variance	7.70	13.70	13.81	16.22	51.42

P(W)=0.2

Count	120	120	120	120	480
Sum	631	702	861	813	3007
Average	5.26	5.85	7.18	6.78	25.06
Variance	11.99	15.153	17.47	17.59	62.21

P(W)=0.1

Count	120	120	120	120	480
Sum	957	1004	1137	1057	4155
Average	7.98	8.37	9.48	8.81	34.625
Variance	17.32	16.89	18.34	16.19	68.73

P(W)=0.0

Count	120	120	120	120	480
Sum	1322	1412	1467	1505	5706
Average	11.02	11.77	12.23	12.54	47.55
Variance	13.13	12.33	9.44	9.75	44.64

Total

Count	1320	1320	1320	1320
Sum	219	1513	2066	2558
Average	1.83	12.61	17.22	21.32
Variance	133.50	191.98	176.27	201.44

ANOVA

Source of Variation	SS	df	MS	F	P-val	F crit
Sample	192490.92	10	19249.09	1204.44	0	1.83
Column	2309.97	3	769.99	48.18	0	2.61
Interaction	1847.23	30	61.57	3.85	0	1.46
Within	83680.60	5236	15.98			
Total	280328.72	5279				

APPENDIX I: MULTIPLE LINEAR REGRESSION

The regression equation is
MOV = - 11.6 + 1.90 P(W) + 0.573 Delay

Predictor	Coef	Stdev	t-ratio	p
Constant	-11.6052	0.1745	-66.51	0.000
P(W)	1.89587	0.01781	106.45	0.000
Delay	0.57348	0.05037	11.38	0.000

s = 4.092   R-sq = 68.5%   R-sq(adj) = 68.5%

LIST OF REFERENCES

1. Arbogast, G.W., and Britan, R., "Academia Rides the Changing Tide of C^3 I," *Signal*, v.47, May 1993.

2. Porter, G., "T^4 Introduction," unpublished paper, 23 March 1993.

3. Porter, G., "Critique of 1991 T^4 Experiments," unpublished paper, 23 March 1993.

4. Porter, G., "T^4 Simulation," unpublished paper, 23 March 1993.

5. Neter, J., Wasserman, W., and Kutner, M.H., Applied Linear Statistical Models, 3d., Irwin, 1990.

6. Devore, J.L., *Probability and Statistics for Engineering and the Sciences*, 3d ed., Brooks/Cole Publishing Company, 1991.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Technical Information Center Cameron Station Alexandria VA 22304-6145	2
2.	Library, Code 052 Naval Postgraduate School Monterey CA 93943-5002	2
3.	C3 Academic Group, Code CC Naval Postgraduate School Monterey, California 93943-5000	1
4.	Superintendent, Code OR/SM Attn: Prof. Michael G. Sovereign Naval Postgraduate School Monterey, California 93943-5000	3
5.	Mr. Gary Porter 620 Spazier Avenue Pacific Grove, California 93950	4
6.	Superintendent, Code OR/KE Attn: Prof. William G. Kemple Naval Postgraduate School Monterey, California 93943-5000	1
7.	Mr. Jeffery S. Richardson 2220 North Joni Drive Layton, Utah 84040	1
8.	LT E.M. Zarrillo 1724 Tilton Road Northfield, New Jersey 08225	1