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PARAMETRIC COST ESTIMATION UTILIZING
DEVELOPMENT-TO-PRODUCTION RELATIONSHIP
APPLIED TO THE ADVANCED AMPHIBIOUS
ASSAULT VEHICLE

by

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This thesis examines the relationship between development unit cost and production unit cost. Historical data from seven armored tracked vehicle programs is used to test the relationship. A study of this relationship is useful when production has not begun and the estimator wants a means to estimate production costs. Using data from the seven programs, parametric estimating techniques are used to examine the relationship between production cost and selected independent variables to determine which provide the best estimators of cost.

The data is examined for both disjoint and sequential learning curve theories. The resulting cost estimating relationships (CERs) for each model are explained in terms of how the respective models measure development unit cost and production unit cost.

The final CERs provide insight into Advanced Amphibious Assault Vehicle (AAAV) production cost and possible acquisition strategies.

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Parametric Cost Estimation Utilizing Development-to-Production Cost Relationship Applied to the Advanced Amphibious Assault Vehicle

by

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Submitted in partial fulfillment
of the requirements for the degree of

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ABSTRACT

This thesis examines the relationship between development unit cost and production unit cost. Historical data from seven armored tracked vehicle programs is used to test the relationship. A study of this relationship is useful when production has not begun and the estimator wants a means to estimate production costs. Using data from the seven programs, parametric estimating techniques are used to examine the relationship between production cost and selected independent variables to determine which provide the best estimators of cost.

The data is examined for both disjoint and sequential learning curve theories. The resulting cost estimating relationships (CERs) for each model are explained in terms of how the respective models measure development unit cost and production unit cost.

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I. INTRODUCTION

A major consideration in the decision making process for continuing or canceling a weapon system is an estimate of cost. Too often Department of Defense (DoD) weapons systems acquisitions have been plagued by unfavorable press associated with disparity between proposed and actual costs. This disparity has tended to create an impression of poor management of public funds.

In making decisions, policy makers must weigh the potential value of the system under consideration against an estimate of its cost. As the DoD budget shrinks in response to a changing global threat, the services and their program advocates need to be very precise in defending their programs.

A critical part of this process is an accurate estimate of each program's cost. Program advocates cannot afford to have their programs questioned because of faulty estimates. The Navy's A-12 program is an example of a program that would have filled a recognized national security requirement by replacing the aging A-6 aircraft. The program was beset by faulty estimates and cost overruns. As a result, the Secretary of Defense, Mr. Cheney, canceled the program.

Program cancellation can have long-term implications in a program acquisition environment where it can take a program ten years to get from concept exploration to production.

Precious time can be lost in getting weapon systems to the operating forces who will use them. Another result from faulty cost estimates is that DoD cost analysts do not have the information necessary for choosing programs among competing alternatives. Accurate cost estimates are critical to evaluating programs with respect to the Department's resource allocation decisions. (Fisher, 1970, p.70)

Large growth in costs during a system's development and production seriously undermines both Congress' and the public's faith in DoD. Such cost growth significantly impairs DoD's ability to budget for necessary quantities and types of weapons systems needed to meet mission requirements. One method of increasing the accuracy of cost estimates is with the use of parametric cost estimation techniques.

This research examines the relationship between development costs and production costs. Historical data from seven armored tracked vehicle programs will be used to test the relationship. A study of this relationship is useful when production has not yet begun and the estimator wants a means to estimate production costs. This research will also develop a Cost Estimating Relationship (CER) for use in estimating the cost of next-generation U. S. tracked armored vehicles. The purpose of deriving this CER will focus on how development costs and the time frame over which development is conducted affect production cost of the advanced assault amphibious vehicle (AAAV), which is currently being developed for the

Marine Corps. This paper will use parametric cost estimation methods to determine the relationship between the cost of development units and the cost of production units.

The second chapter reviews previous cost estimating work on the AAAV. The third chapter develops the data base. The data base will include cost, quantity and program duration elements for other programs as a basis of comparison. CERs will be developed to include only those independent variables that provide a high degree of statistical validity for the model and retain an intuitive ability for explaining production cost.

II. PROGRAM COST ESTIMATION

A. INTRODUCTION

The purpose of cost estimating is to produce reliable cost estimates for decision makers at all levels. Adequate cost estimation depends on the methods used for making the estimate and the time available. Estimates require a systematic study of the program in question and application of cost estimating knowledge and skills in order to form a valid judgement regarding cost. The resulting estimate provides management with quantitative data for making decisions.

Cost estimation is based on interpretation of observed historical factors relevant to the task to be performed, which are then projected into the future. The projections can be made by several methods. The cost estimator should be guided by the following considerations when choosing a method to generate the cost estimate:

1. Availability of historical data.
2. Level of estimating detail required.
3. Adequacy of technical description of the item being estimated.
4. Time constraints.
5. Purpose of the estimate.

(Acker, 1989, p.9-6)

B. ESTIMATING METHODOLOGIES

The techniques used for estimating programs' costs range from intuition at one extreme to a detailed application of labor and material cost standards at the other. Three common types of cost estimates used in the DoD are parametric estimates, engineering estimates, and analogy estimates.

Parametric estimates are derived by extrapolating costs from actual costs of previous systems and correlating their costs to physical and/or performance characteristics of the system in question. (Stewart and Wyskida, 1987, p.117)

Cost estimation by the industrial engineering , or "bottom up", technique requires detailed studies of labor and material costs at the lowest level of the Work Breakdown Structure (WBS). These estimates are defined as a disaggregated examination of the separate segments of work at a detailed component level and subsequent aggregation of the many detailed estimates into a total. The cost estimate requires thousands of man hours to produce and is not flexible in incorporating design changes. Publicized evidence of frequent cost overruns on highly visible DoD projects have indicated questionable accuracy of the "bottom up" approach. (Batchelder, and others, 1969, p.5)

Analogies depend on the known cost of an item used in prior systems as a basis for estimating the cost of a similar item in a new system. Adjustments are made to known costs to account for differences in relative complexities of performance, design and operational characteristics. (Acker, 1989, p.9-6)

Each type of estimate is useful under certain conditions. Parametric estimates and analogies are particularly suitable when there is limited design information available for the system in question. For most programs the parametric approach or the analogy approach to cost estimating are the only feasible methods prior to or during the concept formulation phase. The absence of detailed information on the nature of work to be performed precludes application of other estimating techniques. Only after detailed contractor proposals are prepared can industrial engineering procedures be applied to develop a cost estimate.

C. PARAMETRIC COST ESTIMATION

Parametric estimating methods allow an analyst to examine the impact on cost of a variety of changes being considered in performance requirements of a system. This can be done at little expense by adjusting performance parameters in the cost equation. This information is particularly important during early phases of the planning and development process. Since parametric estimates are based on the actual cost of previous systems, they are valid in so far as the accuracy and normalization of the data used as input is concerned. (Fox, 1974, p.157) As in all functional estimating models, there must be a logical or theoretical relationship of the variable to cost, a statistical significance of the variables' contributions, and independence of the variables to the explanation of cost. (Ostwald, 1974, p.207)

One method of evaluating a hypothetical relationship is to develop a model that uses parametric techniques to test its validity against other known programs. By using parametric cost estimating methods, the model builder must hypothesize the nature of cost relationships. In other words, it is necessary to determine what are the variables that drive cost for the system.

The approach used in this paper is to develop an initial model encompassing hypotheses that are logical and reflect accurate variable interrelationships. A desirable attribute of a model is that it accounts for cost determinants. The hypothesized CER form should reflect an underlying rationale based upon engineering principles or physical laws that can be defended on grounds other than solely those of statistical correlation.

This procedure is based on the premise that the cost of a weapon system is related in a quantifiable way to the system's physical and/or performance characteristics. Parametric cost estimates can provide reliable estimates during the early stages of development before detailed engineering plans are available. Development of estimating relationships between appropriate variables can be constrained by lack of homogeneous data points. On the other hand, there are any number of explanatory variables which can be considered as cost drivers for the system being analyzed. The challenge for the estimator is in obtaining a consistent definition of many of these characteristics. (Sovereign, p.216)

The next chapter discusses cost estimation as it is related to a specific program, the advanced amphibious assault vehicle (AAAV). This program is in the concept exploration/definition phase and has been the subject of several cost estimates. These estimates, using parametric methods, are reviewed as background for CERs that will be developed in Chapters IV and V.

III. AAAV COST ESTIMATION

A. AAAV PROGRAM BACKGROUND

The Marine Corps has a requirement for replacing its current assault amphibious vehicle, the AAV7A1. The next generation of amphibian vehicles will be required to complement the Landing Craft Air Cushion (LCAC) and medium lift aircraft used by the Marine Corps to transport troops from ship to shore during amphibious assaults. This requirement is based on the mission to support over-the-horizon (OTH) amphibious assaults. OTH amphibious assault is based on the principle that the farther assault waves can be launched from shore, the greater is the area on which the forces could potentially land. In order to be launched from a position over the horizon, the next generation of amphibian vehicles will need to be able to close on the beach at speeds of approximately 20 knots. This makes detection and the forward engagement of an amphibious task force more complicated, and it forces adversaries to defend a much larger area ashore, enhancing opportunities for tactical surprise.

Marine Corps requirements call for a high-speed system that can carry at least 17 Marines, excluding crew members, attain speeds on land equivalent to the M1A1 tank (about 35 mph), travel in excess of 20 knots on water (an increase of over three times the capability of the AAV7A1, have armor capable of defeating 14.5 mm armor-piercing projectiles at 300 meters, and have a weapons system capable of defeating targets at a distance greater than 1500 meters. (Marine Corps Gazette, 1991, p.6)

The Marine Corps is currently considering several options to meet their requirements. They range from a high-water-speed AAAV to an upgraded model of the AAV7A1 (the AAV7A2). Of all the options under consideration, the high-water-speed AAAV has received the most attention. It is currently in the concept exploration phase. The Milestone I Defense Acquisition Board (DAB) meeting is scheduled for February 1992 to determine if the program should continue into a demonstration and validation phase. It is expected that contracts will be awarded to FMC Corporation and General Dynamics, who are participating in the proof-of-concept phase. The Center for Naval Analysis (CNA) determined in an earlier cost and operational effectiveness analysis (COEA) that the high-water-speed AAAV was the most operationally effective system of the options being considered. (Marine Corps Gazette, 1991, p.6)

The AAAV is a major program as defined in DoD Directive 5000.1. As an Acquisition Category (ACAT) I program, the AAAV is subject to specific levels of review and management. The Program Manager (PM), must, among other things, submit cost estimates for review and continuation of the program. The services also provide independent cost estimates to the service and DoD decision makers as separate estimates of program cost. The Naval Center for Cost Analysis (NCA) provides these estimates for Navy and Marine Corps ACAT I and II programs.

As an ACAT I program, the AAAV cost estimates are reviewed by the OSD Cost Analysis Improvement Group (CAIG). The function of the CAIG, as set forth in DoD Directive 5000.4, is to provide the Defense Acquisition Board (DAB) with a review and evaluation of both independent and PM cost estimates that are prepared for presentation at milestone reviews. The object of the independent estimate is to advise decision makers of the reasonableness of the PM's estimate. (Fitzgerald, 1990, p.4-70)

B. THE TREAD MODEL

One cost estimation method available to the analyst for estimating armored combat vehicles is the Tracked-Vehicle Resource Analysis and Display (TREAD) cost model. (Systems Planning Corporation, 1978) This model's purpose is to estimate the life cycle cost of advanced technology armored combat vehicle concepts as well current vehicles. The TREAD cost model is based on the parametric approach, using relationships between system cost and physical characteristics of the system (or subsystem). In the past, many models have estimated hardware cost by combining several subsystems, using weight as the driving variable. This method was considered too crude for the TREAD model, particularly in estimating costs of advanced technology components. To improve on this, the TREAD model uses a test bed vehicle that incorporates features of variable weight, horsepower, suspension stiffness, and fire control systems to study different systems. The TREAD model's value is in providing information on future armored vehicle concepts that contain credible estimates of cost along with effectiveness. (Systems Planning Corporation, 1978, p.1-4)

The total life-cycle TREAD cost model consists of four submodels: a production or hardware manufacturing submodel, an investment submodel that captures other elements of investment, an operating and support (O&S) submodel, and a research and development (R&D) submodel.

The approach is to break down the vehicle system into subsystems and occasionally into components of subsystems. Historical cost data or estimates from experts were then used to estimate cost driving variables based on physical or performance characteristics. From these, CERs were developed which were programmed into a computerized model. In the R&D submodel, the R&D phase was broken down into two distinct phases: Concept Validation and Full Scale Engineering Development (FSED), which could be treated separately. An analogy approach was used to estimate development engineering costs. The production submodel was used to derive the contractor prototype manufacturing cost.

C. AAAV COST ESTIMATION STUDIES

In 1984, the Center for Naval Analysis (CNA) did an Independent Cost Estimate (ICE) for the LVT(X). The LVT(X) program was to be a follow-on vehicle to the AAV7A1. The study used two techniques to estimate development costs. The first method used the TREAD cost model. This model allows estimation of development unit costs by analogy with the M-1 tank program and by factors from the M-1 and other combat vehicle programs. The second method used a CER based on a historical sample of tracked vehicles that estimated development phase costs as a function of production unit costs. (Kusek, 1984, p.4)

In the second method, a CER was established to relate the cumulative average production costs of seven historical tracked vehicle systems to the development costs of those systems. This methodology was used by Advanced Technology, Inc., in an earlier costing effort for the Mobile Protected Weapon System. This model used a combination of parametric, factor, and analogy techniques. The data base established by Advanced Technology was updated to take advantage of the most recent cost data available. The subsequent model estimated total development cost as a function of unit procurement cost.

The cost of the LVT(X) estimated in the study was for a generic vehicle that conformed to the system described in its Required Operational Capability (ROC) issued in 1982. The LVT(X) family of vehicles had the following operating requirements.

- Capable of at least eight mph in calm water and six mph in sea state two
- Transit eight-foot-high plunging surf
- Launch and recover from underway amphibious shipping and landing craft
- Achieve 45 mph on level hard-surface roads
- Keep up with the main battle tank
- Cruising range of 300 miles without refueling

They must also have the lethality and survivability necessary to enable the landing force to attack and destroy enemy forces and beach defenses.

The CNA estimate was based on a slow water-speed vehicle. Subsequent estimates done for the PM have estimated the costs for both slow and fast water-speed vehicles. Estimates for the slow water-speed vehicle are based on the 1982 ROC. The fast water-speed vehicle has a water-speed requirement of 20 mph; other requirements remained unchanged. This is a significant difference in the two vehicles' capabilities.

More recently, three cost estimates have been done on the AAAV to support the Program Manager. In 1987 an average unit rollaway cost estimate was done for the PM for two alternative vehicle designs. The major performance differences between the two concepts is water speed. One concept, designated slow AAAV (SAAAV), will achieve a water-speed of 8-10 mph; the alternative, designated fast AAAV (FAAAV), will achieve a water speed of 20 mph. (AAAV, Average Unit Rollaway Cost Estimate, 1987) This estimate was subsequently updated to include full life cycle cost estimates and was prepared for the PM in response to Milestone 0 requirements. The estimate is a parametric "top down" estimate of the entire life-cycle costs based on statistical comparisons or direct analogies with comparable weapons systems. (AAAV, Preliminary Life Cycle Cost Estimate, 1988)

One area of difference between PM estimates and independent estimates was the size of the ratio between development-to-production cost. This paper analyzes the development-to-production ratio using other tracked vehicle programs to determine how development costs relate to production costs. To examine the relationship, this thesis follows the approach taken in several studies prepared for the Naval Center for Cost Analysis (NCA). These studies examined the CERs for missiles, radar and electronics. (Gardner, and others, 1990) The approach here is to develop an initial model encompassing logical hypotheses that reflect the proper variable interrelationships. This paper is limited to an analysis of the relationship between development unit cost and production unit cost and how this relationship can be used in estimating AAAV production cost. A complete life-cycle cost estimate for the AAAV program is beyond the scope of this paper.

The estimating methodology used in this paper is an extension of previous research into the relationship between development unit cost and production unit cost of tactical missile systems, radar, and electronics. This methodology builds on the earlier models that estimated unit production cost as a function of average unit cost in development and quantity of development units.

The most critical areas in parametric estimating are data base development and the building and application of the cost estimating model. The next chapter describes the programs used for the estimation and data points used to test the hypotheses.

IV. DATA BASE DEVELOPMENT

The basic requirement for estimating costs either by direct analogy or by parametric means is a reliable data base. The quality of an estimate will be no better than the data it is based on. The data collected for this study is structured for use in developing relationships between the prototype manufacturing costs of development units and the recurring costs of production units for seven armored tracked vehicle programs.

A. PROGRAM CANDIDATE SELECTION

The data base consists of cost and quantity data for seven tracked vehicle systems. The size of the data base was determined by the number of systems for which data was available for both development costs and production costs.

Many of the systems have been produced over several years, with upgrades and different variants to the basic vehicle. The upgrades and variants were considered to be modifications to existing systems, so they were not included. The reasoning is that development unit cost of a modified system would be unusually low relative to the other systems as a result of commonality with the original vehicle. The data for the candidate systems is therefore limited to the original models and variants, even though in most cases, the programs continued for many years.

Development and production costs were collected for the candidate systems. In order to make all data points comparable, it is necessary to determine what part of development and production costs should be included. In the case of development costs, the prototype manufacturing cost is used. In the case of production costs, recurring production costs of the vehicle system are used.

Production costs include recurring and non-recurring costs. Recurring costs must be incurred each time a unit of equipment is produced. These costs include, for example, direct labor and direct materials. Non-recurring costs are expended at the beginning of a program to establish the specific capability to manufacture the weapon system. These costs are one-time expenditures and generally include such things as special tooling, special equipment, plant rearrangement, and the preparation of manufacturing instructions. (Acker, 1989, p. 9-2)

These costs can be determined from available data sources, and most accurately reflect the data points necessary to examine relationships between development and production costs. Recurring production costs are a function of the number of units produced, non-recurring costs are not. Non-recurring costs can include costs not associated with the actual production of the unit, as in the case where a contractor is allowed to fund development work on new projects by charging it off as an operating expense of a current project (Batchelder, and others, 1969, p.22). For this reason, recurring production cost was considered the best measure of specific hardware costs for each of the candidate systems. To provide consistency with production cost data, prototype manufacturing cost was chosen as the logical counterpart for development cost data.

The method of determining prototype manufacturing cost for each system was necessarily different for each of the programs because of the data available. Historical data on programs dating back to 1956 were not detailed enough to provide prototype manufacturing cost. Data on current programs, such as the M-1 and Bradley Fighting Vehicle, required analysis of Contract Performance Reports (CPRs) to determine prototype manufacturing cost. Specific details on how this was done are included with the vehicle descriptions.

B. DATA SOURCES

Data points from the following seven armored tactical vehicle programs will be used in examining the relationship between development cost and production cost.

- M-1A1 ABRAMS TANK
- M-60 COMBAT TANK
- M-113 ARMORED PERSONNEL CARRIER
- M-2/3 BRADLEY FIGHTING VEHICLE

- M-109 SELF PROPELLED HOWITZER
- M-110 SELF PROPELLED HOWITZER
- LVT-7A1 LANDING VEHICLE TRACKED

Cost data were collected from several sources. Various editions of Jane's All the World's Armored Vehicles were used to narrow the population for this study. Jane's provided consistent information on program length, upgrades of the same system and general operating characteristics.

This information also included the Research and Development (R&D) periods and the number of prototypes produced for some programs. The R&D periods and prototype quantities for older programs were necessary because contract data obtained for this study did not include this information.

M-1 data was obtained from numerous sources. The Naval Center for Cost Analysis (NCA) provided CPRs from FY80 to FY89 for the M-2/3 and development cost data for the M-2/3. Contractor data was obtained for the M113, M109 and M110. This information contained complete histories of the vehicles from development through production.

M-60 data was obtained from two sources. Development data came from an historical summary provided by NCA, while production data came from a 1988 thesis, "An Evaluation of Competitive Procurement Methodologies Applicable to the Advanced Assault Amphibian Vehicle" (Corcoran, 1988).

LVT-7 data was obtained from a 1974 thesis, "A Case Study of the LVTVP-7 Amphibian Tractor Program" (Bahnmaier, 1974).

Data Source Associates publications provided missing data elements and served as a second source for some current programs. (Nicholas)

C. DATA NORMALIZATION

To be useful for comparative analysis, cost data for the identified programs had to be normalized for consistency with respect to work breakdown structure, escalation indices, and expenditure profiles.

1. Work Breakdown Structure (WBS)

The WBS provides a segregation of recurring costs for development and production units. This segregation was used to reduce ambiguity concerning the content of recurring cost elements between systems in the data base. For development units, costs were identified as prototype manufacturing cost. Production unit costs were the recurring portion of the primary vehicle cost at Level 2 of the WBS.

2. Deflation Indices

Department of Defense approved indices for Army R&D and Army Surface-Weapons and Vehicles were used to normalize data to millions of FY-92 constant dollars. The deflation indices used are shown in Appendix A. R&D deflators are applied to development units and Surface-Weapons and Vehicle deflators are applied to production units.

3. Expenditure Profiles

When actual expenditures were known by year over an R&D phase or production lot, they were used directly. Each year's expenditures were divided by the appropriate year index to obtain FY-92 constant dollars. In cases where actual expenditures occurred over a period of years, escalation was based on the expenditure mid-point of the R&D phase or production lot.

A summary of cost, quantity, and year of development and years of production for the seven programs are provided in Appendix B.

D. DETAILED SYSTEM DATA

Recurring production cost and prototype manufacturing cost will be used as data points. Following are summaries for each of the programs. Along with the summaries are explanations of how cost adjustments were made to ensure comparable data points were used. Included are tables with costs and quantities for each program.

1. M-1A1 Abrams Tank

The M-1A1 Abrams is a four man, highly mobile, fully tracked vehicle, with improved survivability provided by ballistic protection and compartmentalization. It is the United States' current main battle tank. Its mission is to destroy an enemy by using firepower from its 105mm main gun and three secondary systems and by using its mobility and speed. Research and development was begun in 1973. The first units were fielded in 1979.

The data for this program came from U.S. Weapon Systems Costs, 1990. The ratio of development engineering cost to prototype manufacturing cost was provided by the Naval Center for Cost Analysis (NCA) (Collins, 1991). The method used is similar to one used by NCA to derive a ratio of basic vehicle cost for the M-1 and Bradley programs.

Production costs reflect the recurring portion of primary vehicle costs at Level 2 of the work breakdown structure. Development costs are the program's prototype manufacturing cost. It is necessary to isolate prototype manufacturing cost in order to gain an accurate cost of the hardware that went into the development models.

A ratio of development engineering cost to prototype manufacturing cost was used as a factor for adjusting the available development cost data. This was necessary to convert the available data, which included much more than just prototype manufacturing cost, to a smaller number reflecting only prototype manufacturing cost. Development cost for the M-1 was then comparable to the six other programs' development costs. The factor used here was derived by NCA from the Baseline Cost Estimate (BCE) for the M-1. (Collins, 1991)

Dev. Eng./Proto Manuf. = 1.37
Dev. Eng. = 1.37 * Proto Manuf.
Dev. Eng. + Proto Manuf = Proto Manuf + (1.37 * Proto Manuf)
233.92 = 2.37 * Proto Manuf

Proto Manuf = 233.92/2.37 = 98.7

Table 1 provides the development and production cost and quantity data for this program. The fiscal year (FY) is the year the units were produced. In this case eleven prototypes were produced between 1976 and 1978. Quantity (QTY) is the number of units produced for that particular year. The cumulative quantity (CUM QTY) is the cumulative number of units produced from the start of production. This quantity is used to determine learning curve rate and theoretical first unit cost.

The indices used are the Department of Defense approved Army deflators for Reliability, Development, Test & Evaluation (RDT&E) and Surface-Weapons and Vehicles. They are listed in Appendix A. In the case of development units, the Army deflators for RDT&E are used to convert then-year (TY) cost data to constant FY-92$. For the M-1, the development costs were in FY-91$. In the case of production units, the Army deflators for Surface-Weapons and Vehicles are used to convert then-year cost data to constant FY-92$. All programs were converted from the production years shown into FY-92$. Unit cost is the cost divided by the quantity for the given year.

TABLE 1: M-1A1 ABRAMS TANK

FY	QTY	CUM QTY	THEN-YR COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
76-78	11	11	95.0	.962	98.7	8.97
PRODUCTION						
79	110	110	186.4	.520	358.5	3.26
80	309	419	312.7	.581	538.3	1.74
81	569	988	708.8	.641	1105.8	1.94
82	700	1688	743.9	.689	1079.6	1.54
83	855	2543	915.3	.725	1262.5	1.48
84	840	3383	859.9	.748	1149.6	1.36
85	840	4223	916.5	.770	1190.3	1.42
86	790	5013	876.3	.794	1103.6	1.40
87	810	5823	896.8	.823	1089.7	1.34
88	689	6512	830.0	.857	968.5	1.40
89	621	7133	785.0	.892	880.1	1.42
90	636	7769	801.6	.929	862.9	1.36
91	225	7994	359.6	.965	372.7	1.66

2. M-60 Combat Tank

The M-60 Combat Tank is a diesel powered, fully tracked, armored vehicle with a 105mm main gun and four man crew. The M-60 has been improved since its original purchase in 1959, resulting in four model upgrades. Initial production for the M-60 was from 1959 to 1963, when it was upgraded and designated the M-60A1. The M-60 was produced between 1959 and 1983 as the United States' main battle tank.

Cost data for this program was obtained from two sources. Development data came from a historical summary of program costs provided by NCA. Production cost data was contained in a 1988 thesis, "An Evaluation of Competitive

Procurement Methodologies Applicable to the Advanced Assault Amphibian Vehicle" (Corcoran, 1988).

Research and Development costs were not available at a level of detail that would permit identification of prototype manufacturing cost. In order to determine prototype hardware costs that would be consistent with the other programs, it was necessary to determine what portion of the total R&D cost could be allocated to prototype manufacturing cost. To do this, the development cost estimate used for the LVT (X) in the CNA (ICE) was used as a proxy for determining prototype manufacturing cost for the M-60. In the LVT (X) estimate, prototype manufacturing is given as 19% of the total development cost. This was applied to the total R&D costs from the data to come up with the development cost in Table 2.

The development cost listed in Table 2 was compared to results using the same development cost data and the methodology discussed in the M-1 case. This was done to check the validity of using 19% of total development cost as an estimator of prototype manufacturing cost. Applying the same method used for the M-1, total R&D would have been divided by 2.37, plus a factor to account for government support. A factor for government support is necessary because government costs appear to have been included in the total development figure. The results of the two methods were compared. There was less than a three percent difference between the two methods. Hence, the figure using the 19% factor was deemed reasonable.

The production cost data for 1959 and 1960 was given in FY-80$. To convert it to FY-92$, the Army deflator for Surface-Weapons and Vehicles was used. The production cost data for 1963 and all development costs were given in FY-78$. The same method of using the appropriate deflator was used to convert them to FY-92$.

TABLE 2: M-60 COMBAT TANK

FY	QTY	CUM QTY	THEN-FY COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
58-61	1	1	1.1	.508	2.17	2.17
PRODUCTION						
59	360	360	386.9	.581	665.9	1.85
60	885	1245	268.8	.581	462.6	.52
63	505	1750	105.2	.465	226.2	.45

3. M-113 Armored Personnel Carrier

The M-113 is a fully tracked, light armored vehicle which serves as the basic squad carrier (10 troops) for the infantry. It is the base vehicle chassis for a family of vehicles which includes command post variants, cargo carriers, and mortar variants. The M-113 was produced from 1959 until 1982, undergoing several upgrades. Cost data for this program was obtained from an untitled study of the M-113 family of vehicles provided by NCA.

Research and development data did not include contracts which either modified or involved feasibility studies on the basic vehicle. The development costs in Table 3 are for prototypes that were built in the given years. Only original prototype vehicles are included in this data. Other prototypes were used, but were either the result of modifications to existing vehicles or test beds for sub-systems. Inclusion of these vehicles would have reduced the average development cost of these vehicles relative to the other vehicles. The vehicle was upgraded to the M-113A1 in 1969. No upgraded vehicles are included in the data.

Both development and production data was given in FY-78$. Data was converted from FY-78$ to constant FY-92$ using the appropriate deflator.

TABLE 3: M-113 ARMORED PERSONNEL CARRIER

FY	QTY	CUM QTY	FY-78 COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
55	1	1	.12	.508	.25	.25
56-59	4	5	4.8	.508	9.45	2.36
PRODUCTION						
60	900	900	5.6	.465	12.0	.01
61	1680	2580	96.0	.465	206.4	.12
62	3000	5580	155.0	.465	333.3	.11
63	4388	9968	205.9	.465	444.9	.10
64	3867	13835	175.8	.465	378.1	.09
66-68	923	14758	34.9	.465	75.1	.08
69	55	14813	2.5	.465	5.37	.10

4. M-2/3 Bradley Fighting Vehicle

The M-2/3 is a fully tracked, lightly armored infantry and cavalry vehicle. It provides cross-country mobility and fire-power to support mechanized infantry operations. The M-2/3 program started in 1979. Production is scheduled to end in 1993. Cost data for this program was obtained from Cost Performance Reports (CPRs) from FMC Corporation from FY-80 to FY-89.

The available M-2/3 development data needed to be converted to costs that reflected only prototype manufacturing cost. The ratio of development engineering to prototype manufacturing cost was used in the same way that it was described in the M-1 case. The ratio used was 2.25, which was derived by NCA from the Bradley BCE. (Collins, 1991)

Development costs were given in FY-91$. Costs were converted from then-year dollars to FY-92 constant dollars.

TABLE 4: M-2/3 BRADLEY FIGHTING VEHICLE

FY	QTY	CUM QTY	THEN-FY COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
77-83	7	7	16.8	.962	17.5	2.49
PRODUCTION						
80	100	100	47.1	.581	81.1	.81
81	400	500	139.3	.641	217.3	.54
82	600	1100	144.4	.689	209.6	.35
83	600	1700	167.2	.725	230.6	.38
84	600	2300	169.2	.748	226.2	.37
85	655	2955	188.7	.770	245.1	.37
87	662	3617	213.2	.823	259.1	.39

88	555	4172	181.4	.857	211.7	.38

5. M-109 Self Propelled Howitzer

The M-109 system consists of a 105mm howitzer gun mounted on a fully tracked carriage, which is propelled by a diesel engine. It provides direct field support artillery fire for infantry divisions and brigades. This system was produced from 1962 to 1967.

Cost data for this program was taken from "Cost Analysis Technical Report, M108 Howitzer, Light Self-Propelled, 105mm, M109 Howitzer, Medium, Self-Propelled, 155mm" (dated March 1969).

The level of detail for development costs was the same as the M-60. The same methodology used in the M-60 case was used here to arrive at a prototype manufacturing cost.

All data were given in FY-74$. Using the appropriate deflators for development and production units, the data was converted to FY-92$.

TABLE 5: M-109 SELF-PROPELLED HOWITZER

FY	QTY	CUM QTY	FY-74 COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
59	1	1	27.5	.363	75.8	75.8
61	2	3	52.1	.363	143.5	71.8
PRODUCTION						
62	245	245	218.3	.329	663.5	2.70
63	208	453	186.0	.329	565.3	2.72
64	360	813	165.3	.329	502.4	1.39
65	360	1173	134.9	.329	410.0	1.14
66	454	1627	129.2	.329	392.7	.86

67	456	2083	137.2	.329	417.0	.91

6. M-110 Self Propelled Howitzer

The M-110 is an 8-inch howitzer mounted on a fully tracked carriage. It is employed as a general support artillery weapon. The M-110 shares the same power train and chassis as the M-107, which was produced during the same time frame. It was introduced in 1962; production of the original M-110 was completed in the late 1960's. Cost data for this program was obtained from CPRs from 1963 and 1971.

Research and development costs were identified for the M110 vehicle family, which included two other variants. Since all three variants used the same power train and chassis, it was appropriate to include the entire research and development cost. This cost, like the M-60 and M-109, did not allocate prototype manufacturing cost separately. This was handled in the same way the other two programs were.

For all the programs evaluated, only the initial models were considered. Upgrades of programs would have affected the unit costs, and would not have provided an accurate analysis of how production costs are influenced by development costs.

The data in Table 6 indicate a shift in unit cost between 1965 and 1966. There was no mention of a model upgrade during this time in the literature. It can be inferred that there was a change in the program that caused a shift in unit cost. For this reason, units produced from 1966 to 1972 were not included in the regression analysis because the shift in unit price after 1965 apparently indicates that there was a vehicle upgrade.

All data were given in FY-74$. Using the appropriate deflators for development and production units, the data was converted to FY-92$.

TABLE 6: M-110 SELF-PROPELLED HOWITZER

FY	QTY	CUM QTY	FY-74 COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
56	6	6	22.9	.363	63.0	10.5
PRODUCTION						
61	120	120	13.2	.329	40.1	.34
62	231	351	22.2	.329	67.5	.29
63	26	377	1.6	.329	4.9	.19
64	30	407	1.8	.329	5.5	.18
65	86	493	5.2	.329	15.8	.18
66	167	666	11.5	.329	34.9	.21
67	74	734	5.5	.329	16.7	.23
70	39	773	2.7	.329	8.2	.21
71	66	839	4.8	.329	14.6	.22
72	21	860	1.5	.329	4.6	.22

7. LVT-7 Landing, Vehicle Tracked

The LVT-7 is an armored assault amphibian vehicle, propelled by two water jets while waterborne and tracks on land. It was designed to transport troops or stores to the beach from amphibious shipping. The program was begun in 1964 and has gone through upgrades and one service life extension program. Cost data was obtained from a 1974 thesis, "A Case

Study of the LVTP-7 Amphibian Tractor Program" (Bahnmaier, 1974).

Derivation of prototype manufacturing cost was done in the same way as the M-60, M109 and M110. This vehicle was upgraded after the initial four year production run. Data given in FY-74$ was converted to FY-92 constant dollars using the appropriate development and production deflators. Table 7 provides a summary of cost data.

TABLE 7: LVT-7 LANDING VEHICLE TRACKED

FY	QTY	CUM QTY	FY-74 COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
67-69	15	15	14.5	.363	39.9	2.63
PRODUCTION						
71	54	54	6.9	.329	20.9	.39
72	390	444	47.7	.329	145.0	.37
73	420	864	49.9	.329	151.7	.36
74	82	946	9.4	.329	28.6	.35

The next chapter will develop and test hypotheses regarding the relationship between development cost and production cost. Appendices B and C contain summaries of the data points to be used.

V COST MODEL DEVELOPMENT

A. PRODUCTION THEORIES

To develop a relationship between development cost and production cost specific to tracked vehicles, this analysis follows a standard methodology which includes identification, collection and normalization of data, regression analysis to test the hypotheses, and finally, a review of the results.

There are two basic approaches, the disjoint and sequential models which attempt to account for differences between development unit cost and production unit cost. The disjoint model uses a production cost improvement curve that is separate from the development cost improvement curve. It implies that any "learning" that occurs during the fabrication of development units is not transferable to production units, and therefore, will not affect production costs.

The sequential model differs from the disjoint model in that the first unit cost of production units follows the last development unit. The sequential model states that "learning" gained in development is carried over to production. Sequential modeling typically allows a discontinuity, such as a decrease in unit cost, in the improvement curve between the last development unit and the first production unit. Both models allow the slopes of the development learning curve and the production learning curve to be different. (Gardner, and others, 1990, p. 2)

Differences between the two models and how their interpretations can affect unit cost can best be explained in terms of acquisition strategies. Both models offer a method of predicting system cost. The disjoint model suggests a program with discrete phases during development. Phases are introduced as part of acquisition strategy in order to provide periodic program assessment. While the disjoint approach is suitable for ensuring that the projected system is operationally and fiscally sound, the effect of "learning" during development does not carry over to production. The goal during development under this strategy is information; therefore, only information relevant to the specific program goal is sought. (Perry, 1971, p.47)

Figure 1 is a graphic representation of the disjoint model. The first production unit is defined as unit one on the production learning curve. In Figure 1, it is point (T_{1P}). The development learning curve is drawn as flat, or indicating a 100% learning rate. First unit development cost is shown at point (T_{1D}). Development quantity (Q_D) is the number of development units. Figure 1 indicates that there is no carryover of knowledge in producing development units to producing production units; their T_1s are essentially independent.

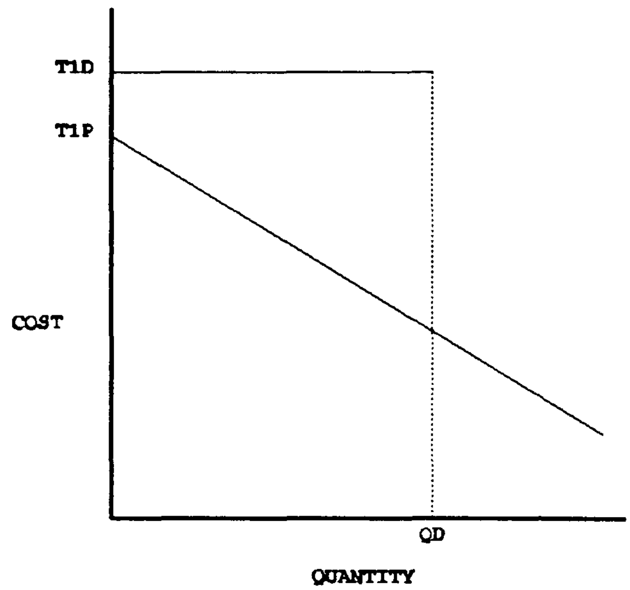


Figure 1: DISJOINT THEORY

The sequential model implies an ongoing assessment, redefinition and readjustment of a program. By doing this, program cost, performance objectives, and schedule changes, among other variables, are evaluated as part of an ongoing effort. As a result of this approach, "learning" during the development phase is transferred to the production phase. (Perry, 1971,p. 42)

A graphical representation of the sequential model is shown in Figure 2. The first production unit, (T_{1P}) is displaced from the y-axis by the number of development units (Q_{D+1}). The additional unit is added because the first production unit is actually the next unit after the last development unit. First unit development cost is shown at point (T_{1D}).

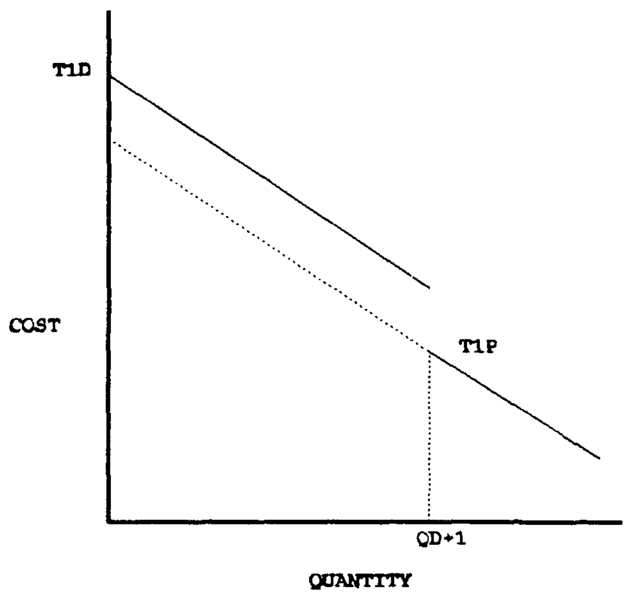


Figure 2: SEQUENTIAL THEORY

As a practical matter, there are few examples of either pure sequential or pure disjoint transitions. Most programs demonstrate varying degrees of each. Prior studies have demonstrated no clear occurrence of one over the other. In this analysis, development and production first unit costs will be calculated using both methods. (Allard, and others, 1990, p.3-3)

B. DERIVATION OF FIRST UNIT COST

The theoretical first unit (TFU) cost is defined as the cost of producing the number one unit in a production sequence. Development units are produced first.

Of the programs being studied, only the M-113 and M-109 showed evidence of separate acquisition phases. This is because prototypes were produced over several years for demonstrating different characteristics.

Because no reasonable learning curve could be determined for the other programs, a flat (100%) learning curve was assumed for all the programs during development. This flat learning curve only applies to the disjoint model, where there is no carryover knowledge in producing development units to producing production units. This is a logical assumption, because the number of development units will not directly affect the TFU cost of development units. It is also possible that "learning" may not have occurred between acquisition phases. This would occur if different vehicles were produced during different acquisition phases, such as concept exploration, engineering development, or test prototype. The sequential model allows for learning to be carried over from development to production.

1. Disjoint Model

Production learning curve slopes were determined for each system based on recurring production costs and quantities produced. The system learning curves are provided in Appendix B. The learning curves were used to calculate the TFU cost of production units (T_{1P}).

2. Sequential Model

In crder to determine TFU in the sequential model, it is necessary to include development units with production units to fit a learning curve for each system. The T_{1P} value from the derived learning curve is displaced from the y-axis by the number of development units plus one. The intersection of the y-axis and projected production learning curve is shown as T_{1P} in Figure 2.

3. Comparison of Disjoint and Sequential Values

The TFUs for both models are listed in Table 8. Included in the table are the calculated learning curve slopes and ratio of production-to-development unit cost for each system. TFUs were computed using Parametric Cost Estimating Relationship (PACER) Model software. The production TFUs will be used as the dependent variable in the CER. Production TFUs, (T_{1P}) in Table 8, were calculated for both the disjoint and sequential cases. CERs will be developed using both sets of data. Development TFUs, (T_{1D}) in Table 8, were also calculated for both the disjoint and sequential cases. These data points, among others described in the following section, are evaluated for their contribution as explanatory variables for production TFUs.

Production first unit costs in the disjoint model should be smaller for each system when compared to production first unit costs for each system in the sequential model. This is because the disjoint model does not account for any learning gained in the development phase. Therefore, first unit production costs reflect only the production costs. In the sequential model, development learning is captured by the inclusion of development units in production first unit cost. The data in Table 8 support this in all cases except the M-60. The M-60 was the oldest program observed. There were a limited number of data points available for inclusion in the analysis. These two factors may have contributed to the unusual observation.

One of this paper's areas of analysis is the development-to-production ratio. Table 8 includes this ratio as T_{1P}/T_{1D} for both models. This ratio was initially studied for its validity as a cost predictor for production costs when development costs are known. The interpretation of this ratio is covered in the conclusions.

Table 8: TFU COMPARISON

	DISJOINT MODEL				
SYSTEM	PRODUCTION		DEVELOPMENT		T_{1P}/T_{1D}
	T_{1P}	SLOPE	T_{1D}	SLOPE	RATIO
M-1A1	5.71	.89	8.97	1.00	.64
M-60	10.72	.75	2.17	1.00	4.94
M-113	.50	.88	.25	1.00	2.00
M-2/3	1.93	.87	2.49	1.00	.77
M-109	88.89	.65	75.8	1.00	1.17
M-110	1.83	.78	10.5	1.00	.17
LVT-7A1	.44	.98	2.66	1.00	.16

	SEQUENTIAL MODEL		
SYSTEM	DEVELOPMENT AND PRODUCTION		T_{1P}/T_{1D}
	T_{1P}	SLOPE	RATIO
M-1A1	12.02	.84	1.3
M-60	2.52	.88	1.16
M-113	.79	.86	3.16
M-2/3	3.73	.81	1.50
M-109	100.92	.65	1.33
M-110	41.5	.54	3.95
LVT-7A1	4.82	.75	1.81

C. CER DEVELOPMENT

The objective of the CER is to relate production TFU cost, as the dependent variable, to independent variables that reflect development cost, quantity, and time span for the candidate programs. CERs that are developed should generate TFU cost when developed from the disjoint or sequential model's data points. The emphasis is on finding a good statistical relationship between TFU and the cost-predictive variables, with particular attention paid to determining cost drivers in a program.

1. Dependent Variable

Production TFU is the dependent variable. Because TFUs have been calculated for both disjoint and sequential cases, CERs are developed and evaluated for both cases. Table 8 shows production TFUs for the disjoint and sequential case under "PRODUCTION T_{1P}". Both models will be evaluated for their robustness in estimating cost. The estimated TFU can then be applied by using the appropriate model and learning curve rate to estimate program cost.

In the disjoint case, TFU_D can be used directly to estimate cumulative cost, or specific unit cost for the program in question. To do this, use the standard learning curve function:

$$Y=AX^b$$

where Y = unit cost of X units
A = TFU_D
X = number of units
b = slope coefficient

In the sequential case, TFUs resulting from the CER need to be converted to a TFU value that can be used with the standard learning curve function as described above. To do this use:

$$TFU_D=TFU_S(DevQty+1)^b$$

In the regressions, t1d is used to denote first unit cost of each system in the disjoint model, and t1s is used to denote first unit cost of each system in the sequential model. TFU_D and TFU_S, respectively, are the resulting first unit cost from the disjoint and sequential CERs.

2. Independent Variables

The independent variables chosen had to meet the following criteria: there must be a sound, logical hypothesis describing how the variable affects cost; the value of the variable must be identifiable early on in the program life cycle; and the value of the variable must be identifiable for all the systems in the data base. (Hess, 1987, p.8) The following candidate independent variables have been identified (in parenthesis is the abbreviation used to identify them in running the model):

- Development cost (totdev)
- Development quantity (devqty)
- Average development cost (avgdev)
- Production rate (prodrt)
- Development time span (devts)
- Time between start of development and start of production (devprod)
- TFU of development (t1dev)
- Year development started (devyr)
- Year production started (prodyr)

The values of these variables for each system are shown in Appendix C.

Before a regression is run, it is necessary to ensure that none of the independent variables are highly correlated. A necessary assumption for the multiple regression model is that no exact linear relationship exists among two or more of the independent variables. Table 9 is a correlation matrix of independent variables for the weapon systems. The instances where independent variables are highly correlated will result in dubious estimated regression coefficients as well as selection of variables that produce illogical results. This table shows that average development cost and total development cost, average development cost and TFU of development units, total development cost and TFU of development units, year development started and year production started are all highly correlated. The relationship between development costs is understandable in that all three are measures of some aspect of the systems development cost. In the case of the actual years of starting development and production for each system, a more precise measure of this relationship turned out to be the time span between starting development and starting production.

TABLE 9: CORRELATION MATRIX OF COST DRIVERS

	avgdev	t1dev	totdev	devqty	prodrt	devts
t1dev	1.000					
totdev	0.940	0.941				
devqty	-0.332	-0.327	-0.089			
prodrt	-0.210	-0.230	-0.370	-0.271		

devts	-0.435	-0.444	-0.531	0.051	0.695	
devprod	-0.219	-0.213	-0.177	0.114	-0.351	-0.373
devyr	-0.226	-0.216	-0.039	0.573	-0.363	0.352
prodyr	-0.247	-0.237	-0.043	0.643	-0.321	0.356

	devprod	devyr
devyr	-0.035	
prodyr	0.036	0.989

Including two or more of the same measures of development cost will degrade the model's predictive value for hypothesis testing. The same is true for including both year development started and year production started. Using this information to narrow the choices of independent variables, a series of multiple regressions was performed using Minitab statistical software. The regressions were used to determine the best relationship between one or more of the independent variables and TFU for both disjoint and sequential models. Two sets of regressions were done to allow comparison between model results.

D. CER RESULTS

The Minitab statistical program provides detailed output to evaluate the significance of the regression equations. Appendix D provides detailed description of regression procedures. The following general criteria were used in judging the output CERs. A t-ratio greater than two for independent variable's coefficient is acceptable for judging whether or not a variable is useful in explaining cost. An R^2 greater than 80 percent, and an F-value of four or more were additional criteria used in evaluating the validity of the generated regression equation.

Beginning with the sequential model data, variables were added to the model one by one. Variables that did not provide a statistically significant level in explaining cost were eliminated from the model. For both models, the average development cost, total development cost and TFU of development units were evaluated in turn with the other variables to determine which measure of development cost was the strongest cost predictor. Additionally, the years of starting development and production were substituted for one another in the model to determine if either, taken separately, would be significant.

A summary of the Minitab stepwise regression of the disjoint model is shown in Table 10 and the sequential model in Table 11.

TABLE 10: STEPWISE REGRESSION OF TFU (DISJOINT)

STEP	1	2
CONSTANT	-1.544	4.301
tldev	1.175	1.143
T-RATIO	12.64	15.22
devprod		-2.7
T-RATIO		-2.01
S	6.20	4.89
R-SQ	96.96	98.49

TABLE 11: STEPWISE REGRESSION OF TFU (SEQUENTIAL)

STEP	1	2	3	4
CONSTANT	4.081	-9.540	5.246	7.345

avgdev	1.343	1.423	1.324	1.313
T-RATIO	7.64	16.02	17.60	31.12
devprod		6.23	4.69	4.85
T-RATIO		4.07	3.73	6.88
devts			-3.3	-4.9
T-RATIO			-2.30	-4.94
prodrt				0.0057
T-RATIO				2.76
S	11.3	5.59	3.89	2.17
R-SQ	92.12	98.47	99.44	99.88

1. Disjoint Model

The final CER for the disjoint model is:

$$TFU_D = -1.54 + 1.18\,t1dev$$

Inclusion of time between start of development and start of production (devprod) as an independent variable adds to the model's fit to the data as evidenced by the increase in R^2. However, in considering this method of calculating the disjoint TFU, a variable containing the time between development and production is not appropriate. It is therefore not included in the final CER. The final model explains TFU_D as a function of TFU of development units.

2. Sequential Model

The CER for the sequential model is:

$$TFU_S = -9.54 + 1.42\,avgdev + 6.23\,devprod$$

As with the disjoint model, the independent variables chosen were examined from an intuitive standpoint for their ability to explain the original hypotheses. Development time span (devts) is defined as the time from the beginning of development to the end of development. This variable was not included because it seems redundant when the variable for time between start of development and start of production (devprod) is included. Additionally, the inclusion of development time span does not significantly increase the size of the explained variation. Production rate (prodrt) was also not included in the final equation because it does not significantly increase the explained variation, nor does it strengthen the intuitive explanation of the model. The final equation contains average development cost (avgdev) and time span between development and production to predict TFUs. The inclusion of a variable that explains time spent in development is compatible with this model. The sequential model allows for carryover of knowledge gained during development. This explains the existence of a variable that accounts for cost as a function of the time spent in development.

Appendix E contains the detailed output of the two regression models.

VI CONCLUSION

The methods and procedures employed in this study have demonstrated that a relevant model can be developed to describe the relationship between development unit cost and production unit cost. Seven armored tracked vehicle programs were used to test this relationship. The findings were applied to the AAAV program. Initially, emphasis was placed on looking at the ratio between development cost and production cost in these programs. This was one area of difference between work done by the AAAV Program Office and estimates completed by NCA. Empirically, the ratio did not demonstrate any predictive value for determining cost and these efforts were not included in this paper.

The data was used to examine the relationship between production cost and selected independent variables to determine which variables might provide the best estimators of cost. Cost estimating relationships (CERs) were developed for disjoint and sequential models. The differences in the models attempt to account for differences in development unit cost and production unit cost. These differences are instructive in how to apply the final CERs.

The disjoint model implies a program conducted in discrete phases, with pauses that allow for program reassessment. By separating the development cost curve from production cost curve, there is no transfer of "learning" between phases. The resulting CER for the disjoint case indicates that first unit production cost is a function of first unit development cost.

This CER is applicable to programs developed in an environment of constrained resources. The goal in the development phase is to build a system that has demonstrated satisfactory performance and has had its requirement revalidated. At that point, production can proceed with confidence that major changes will not occur. The unit cost savings associated with learning gained during development is not necessarily transferable to production because of the discrete phases.

The sequential model implies that learning gained in development is carried over to production. As with the disjoint model, production cost is a function of development cost. The final CER also includes a term for time between the start of development to the start of production. In the course of development, weapon systems may require changes in performance objectives, or they may only be technically feasible at much greater cost. Changes made to the operating requirement will expand the time in the development phase. This factor is captured in the sequential model.

A. RECOMMENDATION

The sequential model CER is most applicable for estimating the AAAV program. Both high water-speed and slow water-speed vehicles have been demonstrated as feasible. The concept exploration phase should conclude in February 1992 with a Milestone 1 decision. The sequential model captures both the time factor in the decision making process as well as the uncertainty in the specific design of the vehicle.

APPENDIX A

ARMY DEFLATORS

YEAR	RDT&E	Surface-Weapon+Vehicle
1973	.333	.298
1974	.363	.329
1975	.401	.353
1976	.431	.380
1977	.468	.420
1978	.508	.465
1979	.557	.520
1980	.613	.581
1981	.664	.641
1982	.700	.689
1983	.727	.725
1984	.752	.748
1985	.776	.770
1986	.798	.794
1987	.822	.823
1988	.852	.857
1989	.887	.892
1990	.924	.929
1991	.962	.965
1992	1.000	1.000
1993	1.036	1.035

Source: U.S. Weapon Systems Costs, 1990

APPENDIX B

CANDIDATE WEAPON SYSTEMS

M-1A1 ABRAMS TANK

DEVELOPMENT FY	QTY	CUM QTY	THEN-FY COST	INDEX	FY-92 COST	UNIT COST
76-78	11	11	95.0	.962	98.7	8.97
PRODUCTION						
79	110	110	186.4	.520	358.5	3.26
80	309	419	312.7	.581	538.3	1.74
81	569	988	708.8	.641	1105.8	1.94
82	700	1688	743.9	.689	1079.6	1.54
83	855	2543	915.3	.725	1262.5	1.48
84	840	3383	859.9	.748	1149.6	1.36
85	840	4223	916.5	.770	1190.3	1.42
86	790	5013	876.3	.794	1103.6	1.40
87	810	5823	896.8	.823	1089.7	1.34
88	689	6512	830.0	.857	968.5	1.40
89	621	7133	785.0	.892	880.1	1.42
90	636	7769	801.6	.929	862.9	1.36
91	225	7994	359.6	.965	372.7	1.66

```
puc     -  *
        -
        -
    2.80+
        -
        -
        -
        -
    2.10+
        -         *
        -
        -    *
        -             *     *
    1.40+                         *    *    *     *   *    *
        -
        -
        +---------+---------+---------+---------+---------+-----Cumq
        0        1500      3000      4500      6000      7500
```

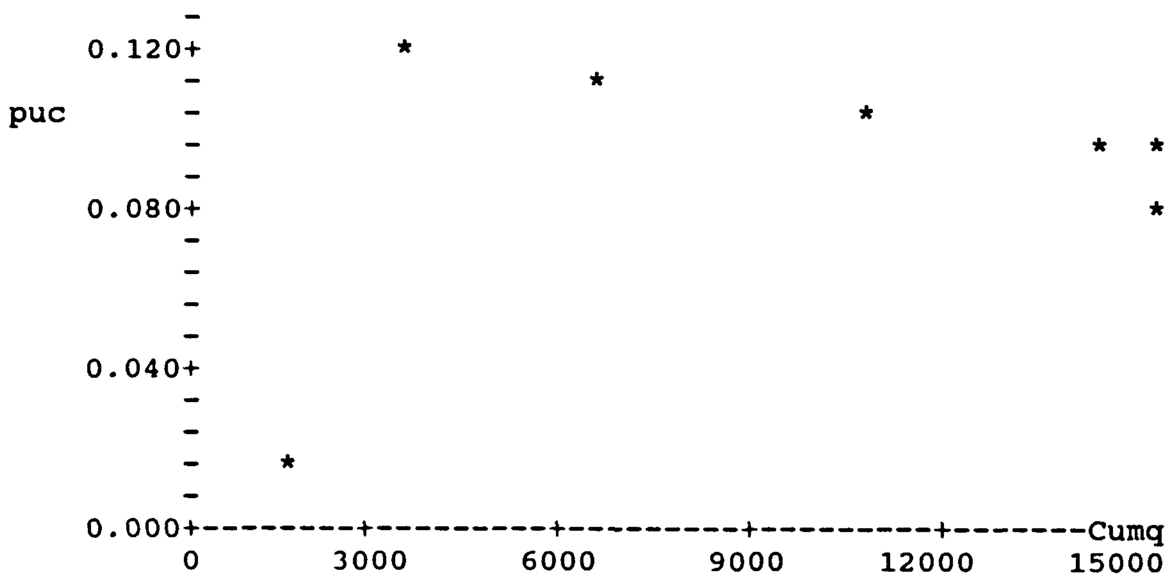
M-60 COMBAT TANK

DEVELOPMENT FY	QTY	CUM QTY	THEN-YR COST	INDEX	FY-92 COST	UNIT COST
58-61	1	1	1.1	.508	2.17	2.17
PRODUCTION						
59	360	360	386.9	.581	665.9	1.85
60	885	1245	268.8	.581	462.6	.52
63	505	1750	105.2	.465	226.2	.45

```
          - *
puc       -
          -
          -
    1.50+
          -
          -
          -
          -
    1.00+
          -
          -
          -
          -
    0.50+                                        *
          -                                               *
          -
          +-----+---------+---------+---------+--------+Cumq
               500       750       1000      1250     1500
```

M-113 ARMORED PERSONNEL CARRIER

DEVELOPMENT						
FY	QTY	CUM QTY	FY-78 COST	INDEX	FY-92 COST	UNIT COST
55	1	1	.12	.508	.25	.25
56-59	4	5	4.8	.508	9.45	2.36
PRODUCTION						
60	900	900	5.6	.465	12.0	.01
61	1680	2580	96.0	.465	206.4	.12
62	3000	5580	155.0	.465	333.3	.11
63	4388	9968	205.9	.465	444.9	.10
64	3867	13835	175.8	.465	378.1	.09
66-68	923	14758	34.9	.465	75.1	.08
69	55	14813	2.5	.465	5.37	.10



M-2/3 BRADLEY FIGHTING VEHICLE

FY	QTY	CUM QTY	THEN-FY COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT						
77-83	7	7	16.8	.962	17.5	2.49
PRODUCTION						
80	100	100	47.1	.581	81.1	.81
81	400	500	139.3	.641	217.3	.54
82	600	1100	144.4	.689	209.6	.35
83	600	1700	167.2	.725	230.6	.38
84	600	2300	169.2	.748	226.2	.37
85	655	2955	188.7	.770	245.1	.37
87	662	3617	213.2	.823	259.1	.39
88	555	4172	181.4	.857	211.7	.38

```
         -  *
         -
     0.75+
         -
puc      -
         -
         -
     0.60+
         -
         -       *
         -
         -
     0.45+
         -
         -                       *                        *
         -                *              *       *
         -
         +---------+---------+---------+--------+-------+Cum
         0        800      1600      2400      3200    4000
```

M-109 SELF-PROPELLED HOWITZER

	FY	QTY	CUM QTY	FY-74 COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT							
	59	1	1	27.5	.363	75.8	75.8
	61	2	3	52.1	.363	143.5	71.8
PRODUCTION							
	62	245	245	218.3	.329	663.5	2.70
	63	208	453	186.0	.329	565.3	2.72
	64	360	813	165.3	.329	502.4	1.39
	65	360	1173	134.9	.329	410.0	1.14
	66	454	1627	129.2	.329	392.7	.86
	67	456	2083	137.2	.329	417.0	.91

```
puc      -     *   *
         -
         -
     2.40+
         -
         -
         -
         -
     1.80+
         -
         -
         -                    *
         -
     1.20+                         *
         -                                             *
         -                                   *
         -
         +--------+---------+---------+---------+-------Cumq
                 700     1050       1400       1750   2100
```

M-110 SELF-PROPELLED HOWITZER

	FY	QTY	CUM QTY	FY-74 COST	INDEX	FY-92 COST	UNIT COST
DEVELOPMENT							
	56	6	6	22.9	.363	63.0	10.5
PRODUCTION							
	61	120	120	13.2	.329	40.1	.34
	62	231	351	22.2	.329	67.5	.29
	63	26	377	1.6	.329	4.9	.19
	64	30	407	1.8	.329	5.5	.18
	65	86	493	5.2	.329	15.8	.18
	66	167	666	11.5	.329	34.9	.21
	67	74	734	5.5	.329	16.7	.23
	70	39	773	2.7	.329	8.2	.21
	71	66	839	4.8	.329	14.6	.22
	72	21	860	1.5	.329	4.6	.22

```
          - *
puc       -
          -
          -
   0.300+
          -                        *
          -
          -
          -
   0.250+
          -
          -                                                  *
          -                                                  *
          -
   0.200+                                            *
          -                              *        *
           --------+---------+---------+---------+-------Cumq
                  200       300       400       500      600
```

LVT-7A1 LANDING TRACKED VEHICLE

DEVELOPMENT						
FY	QTY	CUM QTY	FY-74 COST	INDEX	FY-92 COST	UNIT COST
67-69	15	15	14.5	.363	39.9	2.63
PRODUCTION						
71	54	54	6.9	.329	20.9	.39
72	390	444	47.7	.329	145.0	.37
73	420	864	49.9	.329	151.7	.36
74	82	946	9.4	.329	28.6	.35

```
       -
  0.390+
       -    *
puc    -
       -
       -
  0.375+
       -                        *
       -
       -
       -
  0.360+                                             *
       -
       -
       -
       -                                                 *
  0.345+
       +---------+---------+---------+---------+--------Cumq
        0        200       400       600       800
```

APPENDIX C

DATA BASE

PROGRAM	t1s	t1d	avgdev	t1dev
M-1A1	12.020	5.710	8.97	8.970
M-60	2.520	10.720	2.17	2.170
M-113	0.794	0.504	1.94	.246
M-2/3	3.730	1.930	2.49	2.490
M-109	100.920	88.890	73.80	75.800
M-110	41.500	1.830	10.50	10.500
LVT-7A1	4.820	.442	2.66	2.660

PROGRAM	totdev	devqty	prodrt	devts
M-1A1	98.70	11	153.4	3
M-60	2.17	1	437.5	3
M-113	9.69	5	1851.6	5
M-2/3	17.50	7	521.5	5
M-109	219.30	3	326.8	2
M-110	63.00	6	98.6	1
LVT-7A1	39.90	15	236.5	3

PROGRAM	devprod	devyr	prodyr
M-1A1	1	76	79
M-60	1	58	59
M-113	1	55	60
M-2/3	3	77	80
M-109	1	59	62
M-110	5	56	61
LVT-7A1	2	67	71

Dependent Variable

- TFU of production, sequential model (t1s)
- TFU of production, disjoint model (t1d)

Independent Variables

- Development cost (totdev)
- Development quantity (devqty)
- Average development cost (avgdev)
- Production rate (prodrt)
- Development time span (devts)
- Time between start of development and start of production (devprod)
- TFU of development (t1dev)
- Year development started (devyr)
- Year production started (prodyr)

APPENDIX D

REGRESSION ANALYSIS

The statistical analysis for this thesis was done using Minitab statistical software. Minitab contains the statistical capability for establishing estimating relationships, conditions necessary for valid regression analysis, development of normal regression equations and the statistical criteria to determine validity of the final results. The output provided by Minitab includes values of least squares coefficients and their standard errors, t-ratios, F-value, and coefficient of determination for each regression. As specific criteria for judging the validity of the regression, they are discussed in greater detail in the following paragraphs.

The dependent variable, in this case, cost, is a function of a series of independent variables (X_1, X_2, . . . X_i) and an error term. The multiple regression model has the following form:

$$Y=\beta_1+\beta_2X_2+\beta_3X_3+\ldots\beta_iX_i+\varepsilon$$

Y is the dependent variable, the X's are the independent variables, the βs are the coefficients of the X's, and ϵ is the error term.

The least squares line minimizes the residual (or error) sum of the squares by calculating partial derivatives with respect to the unknown parameters (β_i). The resulting estimates ($\hat{\beta}$) are used to obtain an estimate of variance (s^2), known as the standard error of the estimate. (Pindyck, and others, 1976, p.57)

The smaller the standard error, the better the estimating equation. In choosing independent variables, it is best to select those which, in combination, result in the minimum standard error. (Stewart, and others, 1987, p.112)

The t-ratio is used as a test of each coefficient to determine whether or not its corresponding independent variable X_k has any effect on the dependent variable Y. A low t-ratio implies that the dependent variable is not linearly dependent on the relevant explanatory variable. For this thesis an absolute value of the ratio less than two indicates a lack of significance; in other words, it has no effect on the value of the dependent variable.

The coefficient of determination, R^2, measures the proportion of variation in the dependent variable that is explained by the regression equation. It is typically considered a measure of how well the model fits the available data. For this thesis an R^2 of 80 percent or more is considered acceptable. That is, 80 percent of the variance of the dependent variables is explained by the regression. (Intriligator, 1978, p.126)

One of the problems in deriving a meaningful CER is the problem of having independent variables with high degrees of multicollinearity. Multicollinearity arises when two or more variables are highly correlated with one another. The presence of multicollinearity implies there will be very little data in the sample that will provide any confidence in a meaningful result. (Pindyck, and others, 1976, p.68) The data in this thesis was evaluated to preclude multicollinearity which might adversely affect the validity of potential CERs.

APPENDIX E

REGRESSION EQUATIONS

```
The regression equation is for the disjoint case is:
t1d = - 1.54 + 1.18 t1dev

Predictor        Coef        Stdev     t-ratio        p
Constant       -1.544        2.712       -0.57    0.594
t1dev         1.17500      0.09298       12.64    0.000

s = 6.198       R-sq = 97.0%      R-sq(adj) = 96.4%

Analysis of Variance

SOURCE        DF          SS          MS          F         p
Regression     1      6135.0      6135.0     159.70     0.000
Error          5       192.1        38.4
Total          6      6327.1
```

```
        -
      90+                                              *
        -
t1d     -
        -
        -
      60+
        -
        -
        -
        -
      30+
        -
        -
        -  *
        -       *
       0+ * 2    *
        +---------+---------+---------+---------+------t1dev
       0         15        30        45        60
```

The regression equation for the sequential case is:
tls = - 9.54 + 1.42 avgdev + 6.23 devprod

Predictor	Coef	Stdev	t-ratio	p
Constant	-9.540	4.156	-2.30	0.083
avgdev	1.42267	0.08883	16.02	0.000
devprod	6.230	1.531	4.07	0.015

s = 5.588 R-sq = 98.5% R-sq(adj) = 97.7%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	2	8019.8	4009.9	128.41	0.000
Error	4	124.9	31.2		
Total	6	8144.7			

SOURCE	DF	SEQ SS
avgdev	1	7502.5
devprod	1	517.3

```
        -
     105+
        -  B                                              A
        -
        -
        -
      70+
        -
        -
        -
        -    B   A
      35+
        -
        -
        -  B    A
        -  B3
       0+  4
        +---------+---------+---------+---------+---------+
        0        15        30        45        60        75

        A = tls vs. avgdev        B = tls vs. devprod
```

REFERENCE LIST

Advanced Assault Amphibious Vehicle, Average Unit Rollaway Cost Estimate, September 1987.

Advanced Assault Amphibious Vehicle, Preliminary Life Cycle Cost Estimate, 11 May 1988.

Acker, David D., Defense Manufacturing Management Guide for Program Managers, Defense Systems Management College, 1989.

Allard, Scott M., et al. "Electronics Development to Production Cost Relationships," Management Consulting and Research, Inc., April 1990.

Batchelder, C. A., et al. An Introduction to Equipment Cost Estimating, RAND Corp., RM-6103-SA, 1969.

Bahnmaier, William W., Marine Corps Systems Acquisition Management-A Case Study of the LVTP-7 Amphibian Tractor Program, M.S. Thesis, Naval Postgraduate School, Monterey, California, June 1974.

Collins, Rick, Naval Center for Cost Analysis, Telephone Conversation between researcher, 2 October 1991.

Corcoran, Michael A., An Evaluation of Competitive Procurement Methodologies Applicable to the Advanced Assault Amphibian Vehicle, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1988.

"Cost Analysis Technical Report, M108 Howitzer, Light Self-Propelled, 105mm, M109 Howitzer, Medium, Self-Propelled, 155mm", U.S. Army Weapons Command Cost Analysis Office, March 1969.

"Cost Performance Report DA-04-200-ORD-545", M-110 Vehicle Family, June 1963.

"Cost Performance Report DAAG05-70-C0894 ESP", M-110 Vehicle Family, December 1971.

"Cost Performance Reports", Bradley Fighting Vehicle, FMC Corp., 1980-1989.

Fisher, Gene H., Cost Considerations in Systems Analysis, RAND Corp., R-490-ASD, 1970.

Fitzgerald, David M., Program Manager's Guide, Naval Postgraduate School, Monterey, California, 1990.

Fox, J. Ronald, Arming America: How the U. S. Buys Weapons, Harvard University Press, 1974.

Gaioni, Steven and Polley, Allan, Parametric Cost Estimation Applied to Marine Corps Medium-Lift Helicopters, M.S. Thesis, Naval Postgraduate School, Monterey, California, December 1990.

Gardner, Thurman D., et al., "The Relationship Between Tactical Missile's Development Unit Cost and Production Unit Cost," Science Applications International Corporation, September 1990.

Hess, R. W. and Romanoff, H. P., Aircraft Airframe Cost Estimating Relationships, RAND Corp.,R-3255-AF, December 1987.

Intriligator, Michael., Econometric Models, Techniques and Applications, Prentice Hall, Inc., 1978.

Kusek, Pete, "LVT (X) Independent Cost Estimate (ICE)," Center for Naval Analysis, CRM 84-13, August 1984.

Marine Corps Gazette, "AAAV Program Nears Milestone," September 1991.

Nicholas, Ted G., U.S. Weapon Systems Costs, 1990, Data Search Associates, 1990.

Ostwald, Phillip F., Cost Estimating for Engineering and Management, Prentice Hall, Inc., 1974.

Perry, Robert, et al., System Acquisition Strategies, RAND Corp., R-733-PR/ARPA, 1971.

Pindyck, R. S. and Rubinfeld, D. C., Econometric Models and Economic Forecasts, McGraw-Hill Book Company, 1976.

Sovereign, Michael G., "Survey of Project Cost Estimation," Unpublished Manuscript, ND.

Stewart, Rodney D. and Wyskida, Richard M., Cost Estimator's Reference Manual, John Wily & Sons, 1987.

Systems Planning Corporation, "Tracked Vehicle Resource Analysis and Display (TREAD) Cost Model," November 1978.

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