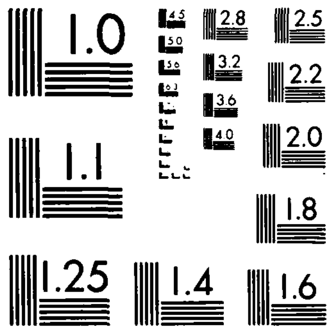
AD-A184 386 LOCK REHABILITATION A PUBLIC INFRASTRUCTURE PROBLEM: 1/2
THE VALUE OF INCREAS (U) MARYLAND UNIV COLLEGE PARK
DEPT OF AGRICULTURAL AND RESOURCE E C E YOE JAN 87
UNCLASSIFIED IWR-87-R-1 DACW72-85-C-0012 F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

US Army Corps
of Engineers
Engineer Institute for
Water Resources

(12)

AD-A184 386

Lock Rehabilitation
A Public Infrastructure Problem: The Value of Increased Productivity In Mean Lockage Performance

January 1987

IWR Report 87-R-1

87 8 2 297

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER IWR Report 87-R-1	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Lock Rehabilitation, A Public Infrastructure Problem: The Value of Increased Productivity in Mean Lockage Performance		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Charles E. Yoe, Ph.D.		8. CONTRACT OR GRANT NUMBER(s) DACW 72-85-C-10012
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Agricultural and Resource Economics University of Maryland College Park, Maryland 21740		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Engineer Institite for Water Resources Casey Building Fort Belvoir, Virginia 22060-5586		12. REPORT DATE January 1987 13. NUMBER OF PAGES 192
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release: distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, Springfield, Virginia 22161

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

lock	capital	navigation benefits	transit time
major rehabilitation	Stall	queue	depreciation
infrastructure	useful life	service time	
deterioriation	asset life	Mississippi River Lock & Dam 13	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The nation's inland waterways infrastructure is aging and in need of rehabilitation and replacement. Economic analyses to date have overlooked the value of increased mean productivity which result from lock rehabilitation. Productivity increases are measured in terms of decreases in the mean time it takes tow to transit a lock. The analysis develops a dynamic model for estimating these values. The quantity of public infrastructure capital, i.e., lock capital cannot be estimated by any of the commonly accepted price or quantity methods due to lack of data. Lock capital is estimated with price

DD FORM 1473, 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

data and estimates of asset depreciation functions. A recursive system of equations with exogenous demand for lockages at the lock to be rehabilitated is estimated to show the effect of lock capital on transit time. An increase in lock capital is shown to decrease mean values of: 1) the time it takes to service a tow 2) queue length and, 3) the total transit time required to pass through a lock. The model is solved for Lock and Dam 13 on the Mississippi River. The value of the improved productivity is minimal and relatively insensitive to variations in model assumptions or the estimation of the quantity of capital. Results indicate a need for data on the physical characteristics of public infrastructure capital so its quantity can be estimated. The value of improvements in infrastructure's mean productivity appear to be insignificant when compared to the value of preventing economic losses which could result from failure or loss of the infrastructure. The importance of an empirical basis for estimating the probability of infrastructure failure is pointed out as is the current lack of data to do this.

LOCK REHABILITATION A PUBLIC INFRASTRUCTURE PROBLEM: THE VALUE OF INCREASED PRODUCTIVITY IN MEAN LOCKAGE PERFORMANCE

by
Charles E. Yoe, Ph.D.

U.S. Army Corps of Engineers
Water Resources Support Center
Institute for Water Resources
Fort Belvoir, Virginia 22060-5586

January 1987

IWR Report 87-R-1

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

THE DEMAND FOR LOCK REHABILITATION

INTRODUCTION

This partial equilibrium analysis takes a step toward providing a framework for providing some of the information that is needed to replace historically and politically based assertions about public infrastructure "needs" with more objective economic analysis. In particular it concentrates on the problem of determining optimal levels and timing of rehabilitation of existing infrastructure capital in the Nation's inland waterways navigation system.

IMPORTANCE OF THE INLAND WATERWAY SYSTEM

There are over 25,000 miles of inland, intracoastal and coastal waterways in the U.S. Of these, the modern inland waterways system includes 11,000 miles of shallow draft channels (18 feet or less) and another 1,000 miles of deep draft channels (18 feet or more). There are over 200 lock and dam sites and thousands of training structures throughout these 12,000 miles.

The existence of this water transportation system is a result of Federal initiatives and activities, in response to specific national needs, over more than two centuries. Responsibility for the design, construction, operation and maintenance of this system has been entrusted by the Congress to the United States Army Corps of Engineers.

The replacement cost of the system is estimated to be $78 billion in 1982 dollars (National Waterways Study, 1983). The system is confronted with steady increases in traffic which contribute to growing and costly delays as lock capacity becomes fully utilized. At the same time many of the water way structures are approaching the end of their engineering design lives and need replacement or major rehabilitation.

Approximately 16 percent of the intercity freight in the U.S. moves by on the waterway. Water transportation provides low cost, energy efficient and safe transit of heavy or bulk commodities. Coal, petroleum products and grains are the top three tonnage commodities, accounting for nearly 55 percent of inland waterway commerce.

Inland waterways are an important part of the nation's transportation network. Though the waterway's share of domestic intercity commerce has remained steady, tonnage has doubled from 216.6 million in 1952 to 536.0 million in 1984.

CAPABILITY OF THE INLAND WATERWAY SYSTEM

The National Waterways Study, a Congressionally authorized review of the nation's waterways (P.L. 94-587), identified the structural reliability of the inland waterway system as a major constraint on the system's ability to handle commercial waterborne traffic. Of 196 U.S. lock sites reviewed, 97 will have exceeded their 50-year design life by 2003. Of these, 48 are considered high use locks which may require major rehabilitation or replacement to insure their reliability. The simultaneous aging of such a large number of locks presents a significant infrastructure problem for the future of commerce and national defense on our inland waterways.

Experience with aging locks indicates that lock closures or stalls and concomitant costly disruption of commercial navigation can be expected to increase as locks age. Stalls can result in increased costs of shipping, delayed shipments, loss of cargo, modal shifts in transportation, significantly higher repair and rehabilitation costs, and higher logistics costs than would be incurred at a lock with a more reliable performance.

Waterway capability or capacity is defined as the maximum tonnage that the waterway can pass per year. Locks generally determine the maximum traffic volume or capacity of the waterway and are the primary constraints in the inland system. It is the capacity of the locks that limits the capacity of the waterway.

Two types of capacity are normally distinguished. Technical or physical capacity is in essence the maximum tonnage that could pass through a lock if the lock operated continuously. Economic or practical capacity is less than technical capacity because economic behavior, in response to lock congestion, contributes to a stochastic arrival of vessels for processing.

This analysis deals with some of the issues that arise in valuing increases in the economic capacity of locks. In particular I estimate the value of the increased productivity that results from an increase in the capital stock of an existing lock through lock rehabilitation.

STATUS OF THE INLAND WATERWAY INFRASTRUCTURE

The National Waterways Study identified a need for substantial investment in the inland waterway system. This need stems from two fundamental forces. First, there is the projected increase in traffic which implies the need for additional capacity within the system to carry the traffic. Next there is the inexorable advance of age and obsolescence which requires major rehabilitation and replacement of existing capacity. Major rehabilitation of existing lock and dam structures to ensure the integrity of the inland waterway system now and into the future is the particular focus of this analysis.

Construction general appropriations to the U. S. Army Corps of Engineers of $955 million in 1985 have fallen in constant 1965 dollars to $235 million or about one-fifth the 1967 appropriation of $966 million. The reasons for this decline are elaborated on by Yoe (1981). The decline in appropriations has also caused capacity expansion and rehabilitation and replacement of existing capacity to decline.

In recent years the Corps' operation and maintenance appropriations in constant dollars have nearly doubled from $179 million in 1967 to $342 million in 1985. Actual 1985 appropriations for operation and maintenance were $1.3 billion. Operation and maintenance expenses for an aging system where rehabilitation and replacement are continuously postponed can be expected to increase.

The Engineer Institute for Water Resources' Report on the Current Status of Selected Waterways (U. S. Army Corps of Engineers, 1985) concludes that slower growth in the demand for waterway services may ease the short term need for investment in capacity-increasing projects. However, the need for timely rehabilitation and replacement of existing capacity will persist.

The report examined 96 locks and found the newest lock chamber at the selected sites will exceed its 50-year design life by the end of the 1980s. The Corps' report finds " a very large lock infrastructure rehabilitation need".

During the last five years nearly $200 million were expended on the rehabilitation of ten locks and dams. The Corps estimates over $300 million will be needed in the next five years for starting or completing another 25 rehabilitation projects. By 1989 there will be 65 old locks with no rehabilitation or replacement as yet planned.

The rehabilitation of locks is not a trivial fiscal issue. A substantial number of locks require rehabilitation and substantial amounts of money have been and will be spent to rehabilitate them. The incidence of lock rehabilitation projects is geographically diverse but concentrated in the Midwest and North Central states. The Corps estimates that for the remainder of the century one in four rehabilitation projects and two out of three rehabilitation dollars will be for the Upper Mississippi locks. The economic impact of rehabilitation projects is more diverse. Costs are born by all taxpayers while benefits accrue most directly to shippers and consumers of their products.

In 1976 there were 1,022 firms operating as carriers on the Mississippi River system and Gulf Intracoastal Waterway. These line-haul carriers are shipper-owned captive carriers, independent for-hire firms and local for-hire independent operators. The government provides an existing right-of-way at no charge to users. Capital requirements for entry into the industry are limited to equipment and working capital. The relative ease of entry, the availability of alternative private transportation to shippers, and the diverse conditions under which water transportation is performed have enhanced competition in the shipping industry.

WHAT IS MAJOR REHABILITATION OF A LOCK?

Major rehabilitation is the construction of infrequent, costly structural rehabilitation works that are intended to extend the useful life of a project. The Corps' Major Rehabilitation Program is limited to the major repair or restoration of main structures such as dams, locks, and breakwaters, exclusive of electrical, mechanical, and other equipment, except where such equipment is essential to and integral with the feature of the project being rehabilitated. The estimated cost of rehabilitation must be $5 million or more and the work must be required to permit the continued use of the project.

THE DEMAND FOR REHABILITATING A LOCK

Congestion at a lock results in delays for vessels using the lock. These delays increase line-haul costs. Low line-haul costs are the major advantage of water transportation systems, which are otherwise slow moving and inflexible in routes. If line-haul costs rise enough the waterways lose their advantage and shippers abandon the waterways for other transportation modes.

Lock rehabilitation is reinvestment in the waterway system. From the standpoint of a single lock, rehabilitation results in an increase in the stock of capital available to produce lock services. The value of the improved quality of services that results from rehabilitation is the focus of this analysis. In particular, this analysis concentrates on the estimation of economic benefits that are currently unquantified and that may be unrecognized.

Advancing age is sufficient to cause concern about the reliability and capability of a lock. Major rehabilitation studies are typically initiated on the basis of physical cues. Experience has shown that age brings with it inevitable deterioration and change in conditions of demand for the services of the lock. Defects in the structures, increasing operation and maintenance activities, declining levels of service quality or quantity are all possible signals that rehabilitation should be considered.

In the current environment of decreasing public infrastructure resources and increasing need, the economic feasibility of infrastructure rehabilitation becomes all the more important. Much of our public infrastructure was built based on political choices and engineering judgment. Is rehabilitation of any particular lock economically feasible? When should the rehabilitation be undertaken? These are some of the economic issues that need to be traded-off against political and engineering values in arriving at rational solutions to the waterway rehabilitation problem.

In the recent past evaluation of rehabilitation projects required neither economic justification nor economic analysis. Current procedures require net welfare gains to proceed with rehabilitation. The purpose of this analysis is to develop a model and estimate the economic value of the increased productivity of lock capital that results from rehabilitation.

Current methods of estimating rehabilitation benefits rely heavily on the value of catastrophic losses from failure(s) of critical lock elements that are prevented by rehabilitation. These losses are not catastrophic in terms of loss of life and property but are costly in terms of the disruption to the transportation system and repair costs of the lock. The methods of estimating these benefits are a matter of some controversy and ongoing research within the Corps.

The value of increased productivity that results from reinvestment in an existing lock under the more certain conditions of normal lock operation has been conspicuously absent from the economic analysis of rehabilitation projects. The single biggest question concerning these effects is their magnitude. If they are substantial then they have been inappropriately overlooked. If they are insignificant in magnitude then confidently estimating the economic feasibility of rehabilitation projects depends solely on the ability to estimate the probability of lock failures and to value them.

Understanding the economic value of "reversing" these wear and tear effects on lock capital builds on an understanding of some physical relationships that are themselves only vaguely understood. As capital deteriorates its total productivity declines. This decline may occur because the output of the stock per fixed set of other inputs has declined or because the service life of the asset has declined, shortening the future flow of services. In the case of lock rehabilitation it is hypothesized that the productivity of a lock declines with the deterioration of lock capital. It is reasonable to hypothesize that the number of tows that can be processed in an hour will decline as the capital available to produce this output declines.

This decline in productivity manifests itself in two significant ways. First, it is hypothesized that as the lock gets older it takes longer to serve a tow. Perhaps the gates close slower and the chamber doesn't fill or empty as fast; the entry and exit may be slower because of defects in the structure. Many physical factors could account for a less efficient, i. e. slower, service time at an aging lock. A second way in which lock productivity declines is through increased frequency and duration of unplanned closures. These phenomena, called stalls, could not be estimated empirically with the data available for this analysis and are the subject of ongoing research.

RESEARCH OBJECTIVES

Age has two basic effects on lock capital. It results in wear and tear on the lock and it increases the probability of catastrophic failure of the lock. To date the latter effect has received all the emphasis in economic analyses, to the exclusion of the former. The primary purpose of this study is to estimate the value of increased productivity in the mean operation of a lock that results from reinvestment in lock capital through rehabilitation. I will develop a partial equilibrium model for estimating these benefits and will demonstrate the magnitude of these benefits by solving the model for an existing project.

In order to achieve the primary objective of the research a number of hypothesized relationships must be tested. Chief among these hypotheses is that an increase in lock capital reduces transit time at a lock. If lock capital is deteriorating over time we expect that it will take longer to transit a lock. If lock capital is increased by rehabilitation we expect that transit times will be shorter. Transit time consists of waiting time in queues plus waiting due to stalls as well as the time it takes to be processed through the lock chamber. Delays from catastrophic failures are not included in this analysis because they are conjectural values that cannot yet be reliably estimated.

Testing this hypothesis requires the building of a model. Building the model requires the specification and testing of numerous other hypotheses. Development and testing of these secondary hypotheses is more effectively left to the body of this analysis.

SUMMARY OF RESULTS

The analysis shows that lock capital is an important determinant of the time it takes to service a tow. Because of this relationship it can be shown that increases in lock capital that result from rehabilitation of a lock lead to decreases in mean service time, queue length, and transit time per lockage.

The functional relationship between transit time and lock capital is part of a dynamic lock rehabilitation investment model. The model is formulated to estimate benefits that accrue as a result of increased mean productivity of the rehabilitated lock due to increases in the capital input. The model is solved for Lock and Dam 13 on the Mississippi River to demonstrate for the first time that these benefits can in fact be estimated.

The magnitude of this overlooked type of benefits proves to be trivially small for the test case. The results of the test case indicate that these benefits are not likely to be large relative to rehabilitation costs or currently estimated catastrophe avoidance benefits except in very unlikely circumstances. Sensitivity analyses show that neither the absolute nor relative levels of benefits change much with different assumptions about the underlying structure of the capital stock variable and other model arguments. The method for estimating the value of improvements in mean lock performance is inexpensive and straightforward to use.

CHAPTER 2

LOCK REHABILITATION MODEL

INTRODUCTION

Development of a lock rehabilitation model builds on the theoretical underpinnings of navigation benefits. Navigation benefits are described in the Federal Inter-Agency River Basin Committee's 1950 "Green Book" as follows:

> The benefits of a navigable waterway are the value of the transportation services provided after allowance for the cost of the associated resources required to make the service available. Such values of transportation service may be derived in terms of the cost of the most likely alternative means of providing the service in the absence of the project....From a public viewpoint, a navigation project will be considered economically desirable if it results in provision of needed transportation services at a lesser total expenditure for goods and services than may be expected to be necessary to provide equivalent service in the absence of the project. On this basis transportation costs rather than transportation rates (i.e., costs to shippers) should be used for measuring benefits whenever possible.

There are no theoretical differences between the economic benefits that accrue to newly built navigation projects or to rehabilitation of existing navigation projects. Two types of benefits commonly accrue to rehabilitation projects. They are different enough to merit separate discussion. Because this research addresses only one of these benefit types I want to briefly describe the other.

If a lock in need of rehabilitation is not rehabilitated there is a risk that a critical element of the lock could fail resulting in a prolonged unplanned closure of the lock. Such an event is called a catastrophe to distinguish it from the more routine occurrence of temporary lock shutdowns called stalls. Catastrophes result in prolonged disruption of navigation traffic and high costs of repair. In the same manner that provision of navigation services results in welfare gains the argument runs that deprivation of these services as a result of a catastrophe results in welfare losses. The expected value of these losses can be estimated in a risk assessment. If these losses can be averted through rehabilitation of the lock and dam the aversion of the expected losses is a benefit.

The major steps in the analysis include generation of subjective probabilities of failure for each component of the system subject to failure with a resultant catastrophe. These probabilities are typically represented by positive sloped exponential curves in probability-time space. Each failure event has an estimated cost associated with it. The cost of failure consists primarily of the repair costs and costs for delayed navigation. The accumulated present worth of expected welfare losses are estimated with the probabilities, cost data and an interest rate. At present the risk assessment is purely conjectural and is the subject of ongoing research. For these reasons these benefits will not be addressed in this analysis.

This chapter proceeds through development of a simple geometric model to a dynamic investment model. The models are based on the premise that changes in the amount of time it takes to transit a lock are good proxies for changes in the price of using the lock. These price changes result in welfare gains or losses. Price declines can be affected through control of the capital stock input that produces the flow of lock services, measured in transit times, through policy choices of the level of rehabilitation effort at a particular lock.

A SIMPLE ECONOMIC MODEL

The model developed in this chapter provides a framework for valuing an increase in lock capital based on improvement in the mean performance of a lock. Figure 2-1 illustrates the nature of the welfare gains that are realized at a typical existing lock where reductions in transit time and therefore shipping costs are the sole source of benefits accruing to rehabilitation capital. A linear derived demand for tow-hours (where a tow-hour embodies the same information as a ton-mile-hour) at a lock is drawn for a profit maximizing firm. The shipper faces private marginal costs of P_1. Social marginal cost, P_2, exceeds private marginal costs because it includes the external costs of lock congestion.

The shipper will demand Q_1 at a private cost of area 4 realizing private benefits of area (1+2+4). Private net benefits are given by area

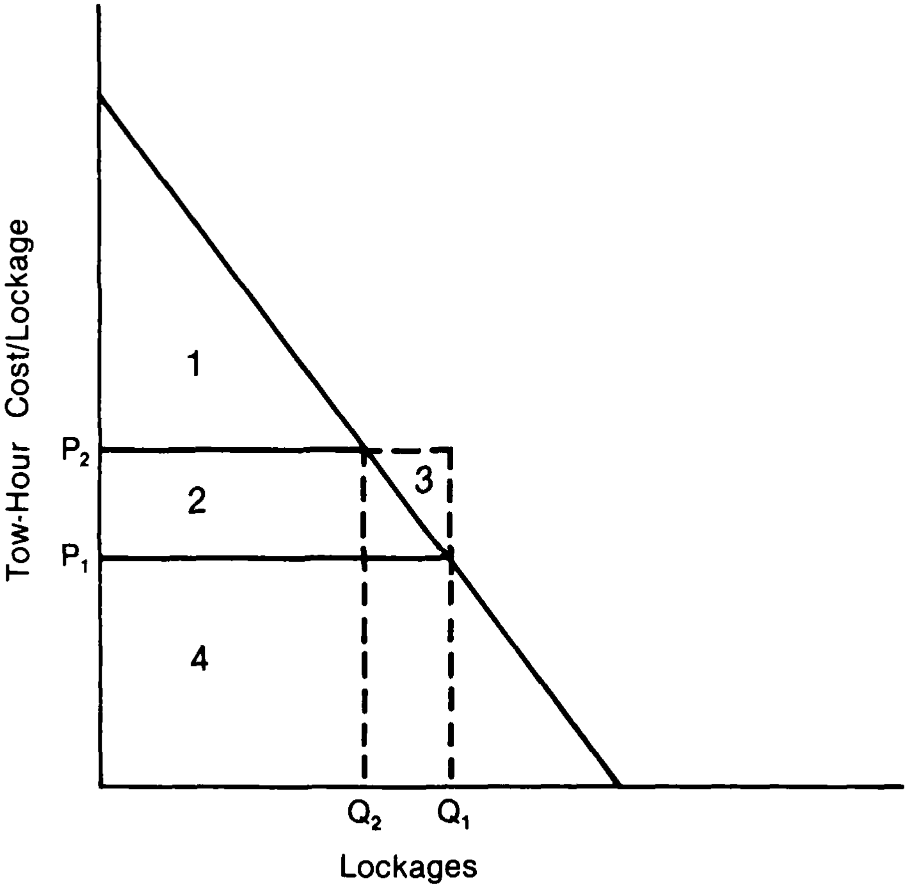


Figure 2-1
PRIVATE AND SOCIAL WELFARE GAINS OF LOCK REHABILITATION

(1+2). Q_1 exceeds the social optimum Q_2 because shippers do not pay the external costs of congestion they impose on others. Social costs include private costs and congestion costs, given by area (2+3).Total social costs are represented by area (2+3+4). Social benefits are identical to private benefits. Net social benefits are given by area (1-3). The difference between net private and net social benefits emphasizes the social welfare costs of the firm's decision to choose too much output.

The intertemporal objective of the firm making decisions about waterway usage is to maximize the present value of profits approximated by a series of areas like area (1+2) over time. Society's objective is to maximize the present value of benefits approximated by areas like (1-3) less the costs of operating and maintaining the lock over time. Costs of constructing the lock can be ignored as sunk costs when considering an existing lock.

If the lock represented in Figure 2-1 undergoes major rehabilitation to improve the reliability and level of service of the lock then the annual number of stalls, annual downtime due to lock-related stalls, and mean service time per lockage are expected to decline. As a result, the total time a tow spends in the locking process will be reduced.

Tow-hour costs are assumed to be linear in time so reductions in transit time are linear proxies for changes in lockage price. A shorter transit time per tow reduces the private costs of a tow-hour in Figure 2-1 by the value of the reduction in transit time. Through integration of the derived demand curve this time reduction can be estimated as an increase in the shipper's profits.

Figure 2-2 emphasizes the differences in the private and social welfare gains from lock rehabilitation. From the firm's perspective the effect of rehabilitation is to reduce the total time required to move through the lock; this reduces costs from P_1 to P_3. Output is increased to Q_3.

Before rehabilitation, the firm chose Q_1 at costs equal to area (5+7+10). After rehabilitation costs equal area (10+11). Resources with a value of area (5+7) are freed for alternative uses because of the lower costs of output.

In real terms a shorter transit time means less labor, fuel and other real resources consumed by a fixed number of tows, in this case Q_1, while processing through a lock. Offsetting this reduction in unit costs is a potential increase in total costs of area (11) due to an increase in the demand from Q_1 to Q_3. Thus total private costs after rehabilitation could be higher if the costs incurred by the new users of the lock offset the cost savings of the Q_1 users of the lock.

Demand for the services of a particular lock is derived from demand for waterway transport that in turn is derived from the supply and demand functions of the goods transported. In Chapter 4 I will demonstrate to a reasonable degree of certainty that the demand for lockages at a specific lock is quite inelastic and the price decrease from rehabilitation will be small. Substitution and output effects in response to rehabilitation are negligible and can be ignored. The dynamic model which follows dismisses the possibility of increases in output like Q_3-Q_1 because demand is exogenous to the rehabilitation decision and its impacts. For the remainder of the discussion of Figure

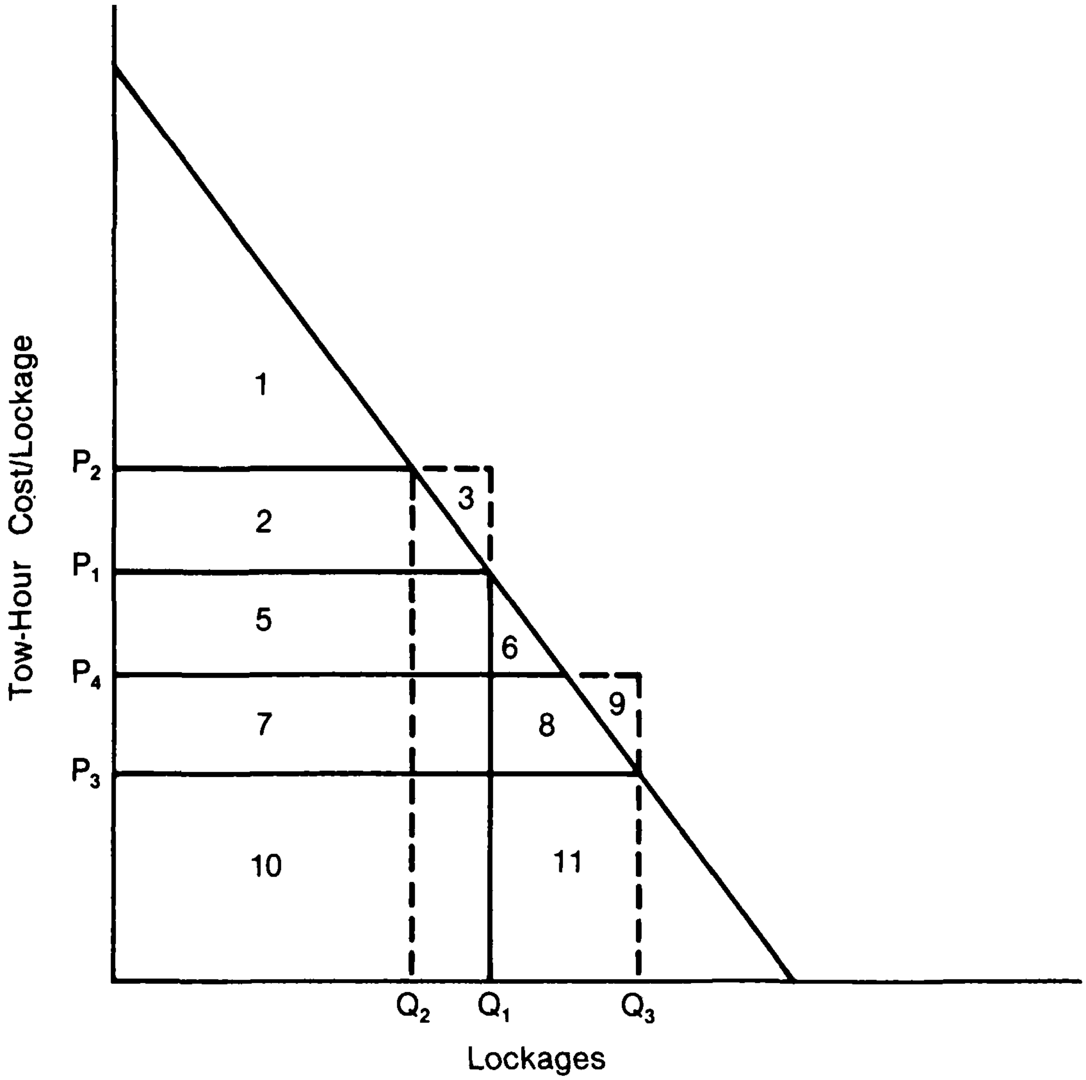


Figure 2-2
WELFARE GAINS WITH CONGESTION EXTERNALITY

2-2, the potential increase in the quantity demanded will be retained as relevant. This helps point out the potential deficiencies of the dynamic model should demand for lockages at a specific lock not behave as I describe in Chapter 4.

For the remaining development of this simple model Figure 2-2 can be interpreted as the aggregate demand for the services of a specific lock. The decrease in transit time results in an increase in gross benefits to the shipping industry from area (1+2+5+7+10) to area (1+2+5+6+7+8+10+11). Net private benefits increase from area (1+2) to area (1+2+5+6+7+8) for a net change in profits of area (5+6+7+8). Area (5+7) is due to lower costs, area (6+8) is due to increased output.

Before rehabilitation social costs of P_2 for Q_1 are defined by area (2+3+5+7+10). Lock rehabilitation results in a change in social costs equal to area (7+8+9+10+11). The decline in unit costs results in reduced total costs of area (2+3+5) while the increase in quantity demanded increases total costs by (8+9+11). There is no a priori information to suggest which of these effects is larger. Hence the net effect on total costs is unknown.

Gross benefits to society are assumed to equal gross private benefits. Gross social benefits also increase by area (6+8+11). Net social benefits, defined as industry profit less congestion costs, differ before and after the rehabilitation. Initially net social benefits are given by area (1-3) and net private benefits, area (1+2). These areas differ by congestion costs or area (2+3). After rehabilitation net social benefits are defined by area (1+2+5+6-9) which also differs from net private benefits after rehabilitation, area (1+2+5+6+7+8), by congestion costs, area (7+8+9).

Comparing net social benefits before and after the rehabilitation, benefits increase by the area (2+3+5+6-9) with the project. Area (2+3-9) reflects changes in congestion costs. The sign of this area is a priori indeterminate because the relative sizes of areas (9) and (2+3) are unknown. In real terms the elimination of congestion costs resulting from traffic levels before rehabilitation could be equalled or even offset by increased congestion costs due to increases in the level of traffic which result from reductions in private costs if demand were endogenous to the model. Figure 2-2 shows only one of many possible shifts in costs. It is not necessary for P_4 to lie below P_1. Neither must P_3 lie below P_1 nor P_4 below P_2.

The shipping industry and society realize different net benefits because they incur different costs. Though both seek to maximize their net benefits the objective functions for the two differ.

As was pointed out in discussion of Figure 2-1 net social benefits must exceed the public costs of operating and maintaining the locks which produce the benefits. It has been shown that net social benefits of rehabilitation increase by the area (2+3+5+6-9). What was not explicitly shown in the figures above in addition to operation and maintenance costs was the cost of rehabilitation. The present value of a series of net benefit areas must exceed the present value of the costs of the major rehabilitation plus all operation and maintenance costs in order for the project to produce any positive net welfare gains.

One potential source of social benefits can become lost in this simple model because public costs have not been shown in the figures. Whether locks are rehabilitated or not, locks have operation and maintenance costs. A rehabilitated lock is generally expected to be cheaper to operate and maintain leading to lower unit costs for society.

A DYNAMIC MODEL

The fundamental economic problem is to identify the level of rehabilitation effort and the optimal time to undertake the rehabilitation that maximizes the net welfare gains just described. This is a dynamic problem.

I have shown how reductions in transit time result in social benefits. Transit time is inversely related to lock capital (Chapter 4) which, as a result of usage and the physical elements, depreciates over time (Chapter 3). As the available capital decreases, transit time increases raising the cost of a lockage.

Lock rehabilitation increases capital stock. With more capital stock available in each year transit times are shorter than they would have been without the rehabilitation. The decrease in transit time means lower lockage costs and the resulting welfare gains.

This relationship can be concisely written

$$(1) \quad \underset{R(t)}{\text{Max}}\ J = \int_{T}^{t_0} ((-(TL^{*}(K))LV - R)e^{-rt})dt$$

s.t.

$$(2) \quad \dot{K}=h(K,R,t)$$

$$(3) \quad K(t_0)=K_0$$

$$(4) \quad K(T)\geq \Gamma_T$$

$TL^*(K)$ is transit time measured in tow hours expressed as a function of the state variable lock capital, K. L is the number of commercial lockages at the rehabilitated lock and V is the cost of a tow-hour. L and V are exogenous to the problem and hence constants. The optimal level of rehabilitation and its optimal timing, R(t), are chosen so as to maximize the present value of accumulated transit time savings evaluated at interest rate r.

The objective functional in (1) maximizes the area

$$(5) \quad (TL(K)-TL^*(K))LV$$

corresponding to area (2+3+5) in Figure 2-2. The asterisk indicates the post-rehabilitation transit time. Area (6-9) is negligible under conditions of exogenous demand as described above and subsequently in Chapter 4. TL(K) is the transit time function for the case of no rehabilitation. The control variable R is not an argument in this function so it does not enter the objective functional.

The transition equation (2) is a net investment function which is linear in R. It describes the net change in lock capital as rehabilitation/gross investment net of depreciation. Equations (3) and

(4) describe boundary conditions with lock capital known and positive in year t_0 and restricted to non-negative values in year T.

Abandonment of the lock would always optimize the functional presented in (1). A transit time of zero ($TL^*=0$) will always maximize the value $-TL^*$ when negative values of TL^* are disallowed. Such transit times will be obtained if there is no traffic, i.e., if the lock is abandoned. In terms of Figure 2-2 a $TL^*=0$ at first seems to imply that net benefits for Q_1 increase by the area (5+7+10). Because a lock operates as part of a waterway system abandoning the lock is not a feasible solution to the problem. Restricting R(t) to non-negative values precludes this form of disinvestment in the waterway system.

The feasible solution set consists of an infinite number of rehabilitation paths over a planning horizon of T years. The annual choice of rehabilitation investment must equal or exceed zero and be less than some practical maximum that varies with the lock under consideration. The optimal solution set is a subset of the feasible set. Rehabilitation will be a discrete and lumpy choice rather than a continuous investment path. Rehabilitation will be undertaken once, if at all, during the planning horizon due to high fixed costs.

Rehabilitation investment, R, is a lumpy variable due to the physical and engineering nature the lock problems and their solutions. Engineering, design, supervision and administration of major rehabilitation work contribute to large overhead costs. Mobilization and demobilization at often hard to reach project sites also constitute a large fixed cost. Temporary disruption of traffic flows during the rehabilitation can be very costly to shippers. In addition the engineering nature of the solutions requires that the work be accomplished all at once over a relatively compact time period. The time path for R will coincide with the axis until it makes a discrete jump to a positive level that is sustained for a short period of time before returning to zero.

R is the control variable. The control path is a set of points in m-space (E^m)

$$(6) \quad (R(t))=(R(t)\in E^m: t_0<t<T)$$

where R(t) is a vector-valued, piecewise continuous function of time and its value at any time is R(t).

At any time t the state of capital stock at an existing lock is characterized by the state variable, K(t). Selection of a time path for rehabilitation effort determines a time path for lock capital which is a set of points in n-space (E^n)

$$(7) \quad (K(t))=(K(t)\in E^n: t_0<t<T)$$

where K(t) is a continuous function of time.

In general K is a vector-valued variable of physical components of a lock. In this analysis both K and R are scalar-valued monetary indices of capital which satisfy the aggregation conditions of weak separability and homotheticity and all relevant theoretical arguments discussed in the next chapter.

To solve the problem described in equations (1)-(4) we form the current value Hamiltonian.

$$(8)\quad HC=(-(TL^{*}(K))LV-R+qh(K,R,t))$$

In this form the problem is to maximize the instantaneous value of R at a time t for the direct value $(-(TL^{*})LV-R)$ and maximizing the indirect value of R over the remainder of the time period through qh where q is the current value costate variable or the shadow price of a unit of K and h is the amount by which K changes at time t. Solving for the first order and transversality conditions of (8) the following are obtained

$$(9)\quad \partial H/\partial R=-1+q(\partial h/\partial R)=0$$

$$(10)\quad rq-(\partial H/\partial K)=\dot{q}=-(LV(\partial TL^{*}/\partial K))-q(\partial h/\partial K)+rq$$

$$(11)\quad \partial H/\partial q=\dot{K}=h(K,R,t)$$

$$(12)\quad e^{-rt}q(T)\geq 0 \quad \text{and} \quad e^{-rt}q(T)K(T)=0$$

where $q=e^{-rt}u$ and u is the present value costate variable.

Condition (9) requires that marginal costs equal marginal benefits. For \$1 of costs there must be \$1 of benefits at optimum. From (9) we obtain

$$(13)\quad q=(1/(\partial h/\partial R))$$

as long as the rate of investment is positive.

Substituting (13) into (10) and setting this equal to the time derivative of (13) yields

$$(14)\quad r(\partial h/\partial R)^{-1} - (\partial h/\partial K)(\partial h/\partial R)^{-1} - \dot{(\partial h/\partial R)}^{-1} = (LV(\partial TL^{*}/\partial K)$$

Equation (14) describes how the value of an additional unit of lock capital changes over time. The right hand side is the net marginal value of lock capital or its contribution to current returns. The left side is the user cost of capital. The term $(\partial h/\partial R)^{-1}$ on the left hand side is the change in rehabilitation costs for an increase in lock capital. This is the marginal cost of lock capital. The first complete term on the left is the opportunity cost of holding lock capital for one period in marginal terms. The second term contains $(\partial h/\partial K)$, a percentage, and is a depreciation factor. The remaining term is the rate of change in the marginal cost of lock capital.

Condition (11) is the equation of motion and (12) is the transversality condition necessitated by a free planning horizon which will identify the time T at which either $K(T)=0$ or the current shadow price of lock capital equals zero. If lock capital is positive (12) will hold where $q(T)=0$. This will occur at some point in the future where the costate variable u equals zero or where the discount factor e^{-rt} is effectively zero.

In practice not all values of R are worth considering. Rehabilitation effort is not a continuous variable. If deteriorating lock capital creates a problem there will typically be a small number of engineering solutions to the problem. The question is which of a few technically feasible rehabilitation alternatives is optimal and when should it be implemented to maximize welfare gains. In the case where R is a single known value the model becomes a special case of the dynamic model where the stream of net benefits accruing to rehabilitation effort is optimized over time. Equation (1) is rewritten for the special case as

$$(15)\quad \underset{t_1}{\text{Max}}\ J = \int_{t_0}^{t_1} (-TL(t)LVe^{-rt})dt + \int_{t_1}^{T} (-TL^{*}(t)LVe^{-rt})dt\ Re^{-rt}$$

subject to the same constraints presented earlier. The problem now is one of choosing the optimal time to implement a known rehabilitation alternative. The necessary condition for a maximum is

$$(16)\quad (TL-TL^{*})LV = rR$$

This condition requires that t_1 be chosen so that the value of the transit time saved, $(TL-TL^{*})$, equals the interest cost of the rehabilitation, (rR). This is simply the familiar requirement that marginal benefits equal marginal costs.

Several potential extensions of the model are worth noting. First, as has already been noted, this model accounts for one type of overlooked benefits to rehabilitation. There are others. Prevention of catastrophic lock failures is an example already mentioned. Other types of benefits which could accrue to a lock rehabilitation project include operation and maintenance cost savings and logistics systems cost savings.

Very briefly, operation and maintenance costs for a rehabilitated lock are generally expected to be lower than they would have been had the lock not been rehabilitated. Rehabilitation of a lock is expected to decrease both the mean and variance of transit times for tows. As deliveries become less uncertain some firms may require less safety stock. Inventory cost savings for the lower stock levels could lead to increased profits. These potential cost savings are often considered perceived costs of shipping in the literature and as such can easily be accommodated in the model by rewriting equation (1) as

$$(17)\quad \text{Max } J = \int_{t_0}^{T} (((-TL^{*}(K) - M^{*}(K) - Z^{*}(K))LV - R)e^{-rt})dt$$

where $M^{*}(K)$ is operation and maintenance costs after rehabilitation and $Z^{*}(K)$ is logistics costs after rehabilitation. These are costs per tow-hour. Lock capital is an argument in each function.

Operation and maintenance benefits are not included in the present model because they are project specific costs that are extremely difficult to estimate in practice. Logistics costs are not included because though rehabilitation of a single lock may affect the mean and variance of transit times at that lock they will have little effect on the mean and variance of transit times over the entire route traveled. In addition, there are currently no data available for analyzing these types of benefits.

The final point to be made about the dynamic model presented above concerns the limitations of the context in which it has been presented.

The model is presented for a single lock. In reality the lock does not stand alone as a functioning unit; it is part of a complex waterway system. The analysis of the economic benefits of lock rehabilitation considered in a system context is far more complex and is left as the subject of future research.

CHAPTER 3

AGGREGATION AND THE QUANTITY OF CAPITAL

INTRODUCTION

The lock rehabilitation problem has been formulated as a dynamic public investment problem. Rehabilitation effort is the investment variable and lock capital is the capital variable in the model. The lock capital variable will influence estimation results and the optimal solution to the rehabilitation problem. The magnitude of the value of the increase in lock capital productivity due to rehabilitation depends on the quantification of capital stock. This chapter reviews the issues involved in estimating the quantity of capital.

THE NEED FOR AGGREGATION

Our understanding of complex relationships in economics, engineering and most areas of endeavor is necessarily limited. When theory and knowledge are adequate data often aren't. We are compelled tc simplify analyses through aggregation of complex variables and phenomena into broader variables and phenomena that are often easier to understand and measure. Conditions under which aggregation of capital yields useful results based on microeconomic theory are very restrictive.

Analysis of the lock rehabilitation problem requires estimates of current and future lock capital stocks. These estimates require aggregation. The fundamental problem with aggregating capital or any economic value is that in doing so information is lost. Concepts valid for the individual production unit when imposed on the aggregate behavior of all the units may no longer be valid. Aggregation trades economic information for tractability. In an analytical or empirical framework this loss of information at the aggregate level can translate into error.

Figure 3-1 shows two types of lock capital, K_1 and K_2 that can be aggregated into a quantity K where

(1) $K=g(K_1,K_2)$

and g is the aggregation function. Line AB represents a specific amount of aggregate capital K based on g. Line CD is a greater amount of K based on g. Any point Z on AB represents a particular combination of K_1 and K_2. Z can be distinguished from any point on CD because it is less of K. However, Z cannot be distinguished from any other point on AB because it is exactly the same amount of K. The inability to distinguish among points on AB makes the loss of information clear. An infinity of combinations of K_1 and K_2 is reduced via g to a single value of K.

K_1 and K_2 can be combined with another input X to produce output Q in the production function

(2) $Q=f(K_1,K_2,X)$

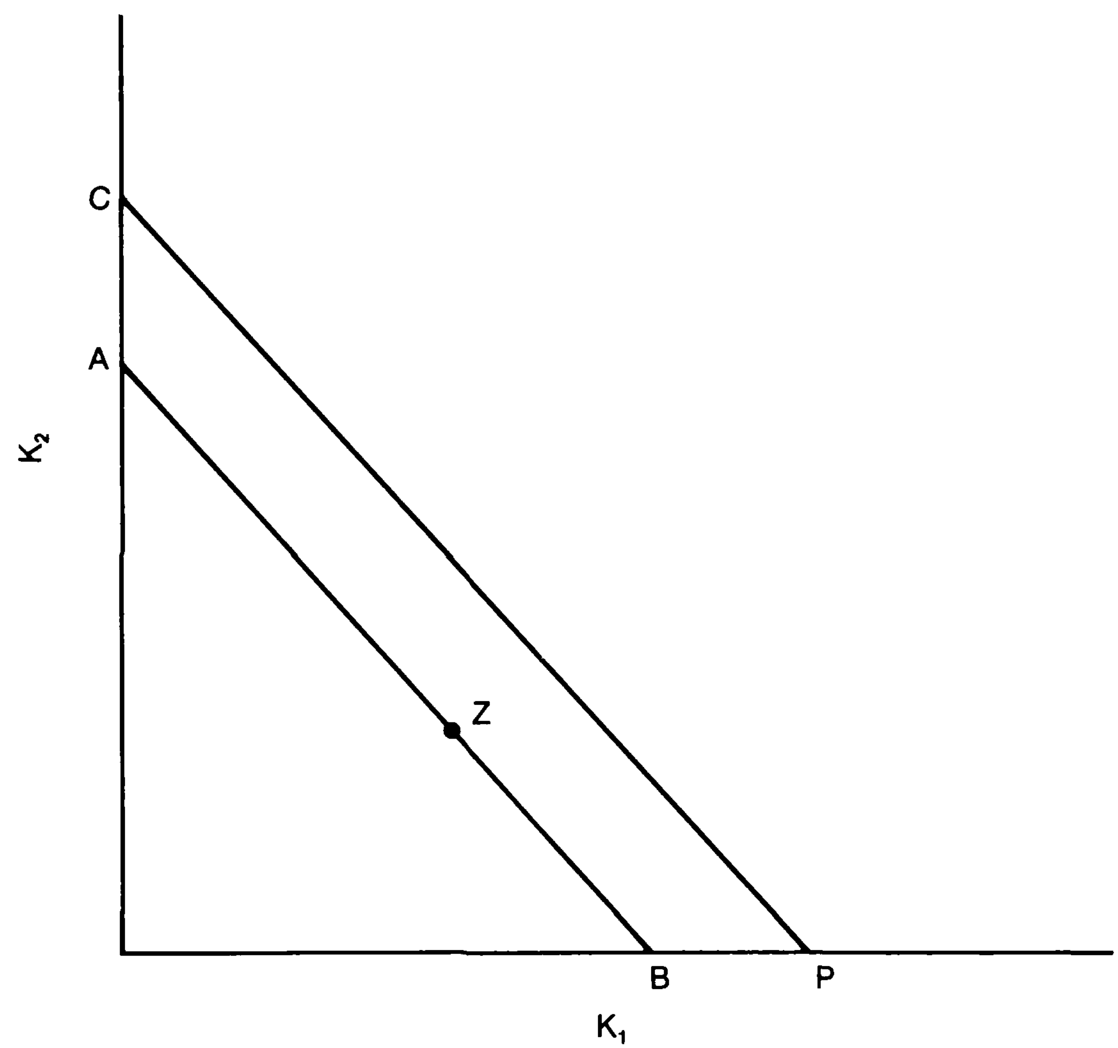


Figure 3-1
LINEAR AGGREGATION FUNCTION

In Figure 3-2 AB represents an aggregate capital input. The isoquant Q_0X_0 shows the amount of output that can be produced with a given quantity of other inputs, X. The isoquant shows the alternative combinations of K_1 and K_2 that produce Q_0 when X is fixed at X_0.

At tangency W the amount of K is an aggregate of the true disaggregated inputs. Any point $Z \neq W$ on AB must lie on a different isoquant even though it is the same level of K represented by W. Holding X constant the same quantity of K produces less and less output as we move away from W on AB in any direction. Thus the same quantity of X and K are capable of producing many different levels of output. This violates the classical assumption that the production function is single-valued.

The assumption of a single-valued efficient technology may be the most important constraint on the producer's choice set. Without it we do not have a monotonic production function and negative marginal products are possible. These results are not permissible if we want to use the neoclassical results that are derived from a well-behaved production function. Because the welfare measurements estimated from the lock rehabilitation model are predicated on cost minimizing behavior and the underlying production function the issue of aggregation is of more than passing interest.

CONDITIONS FOR CONSISTENT AGGREGATION

The primary reason for the loss of information in the above example is the nature of the aggregation function g. In Figure 3-2 a linear

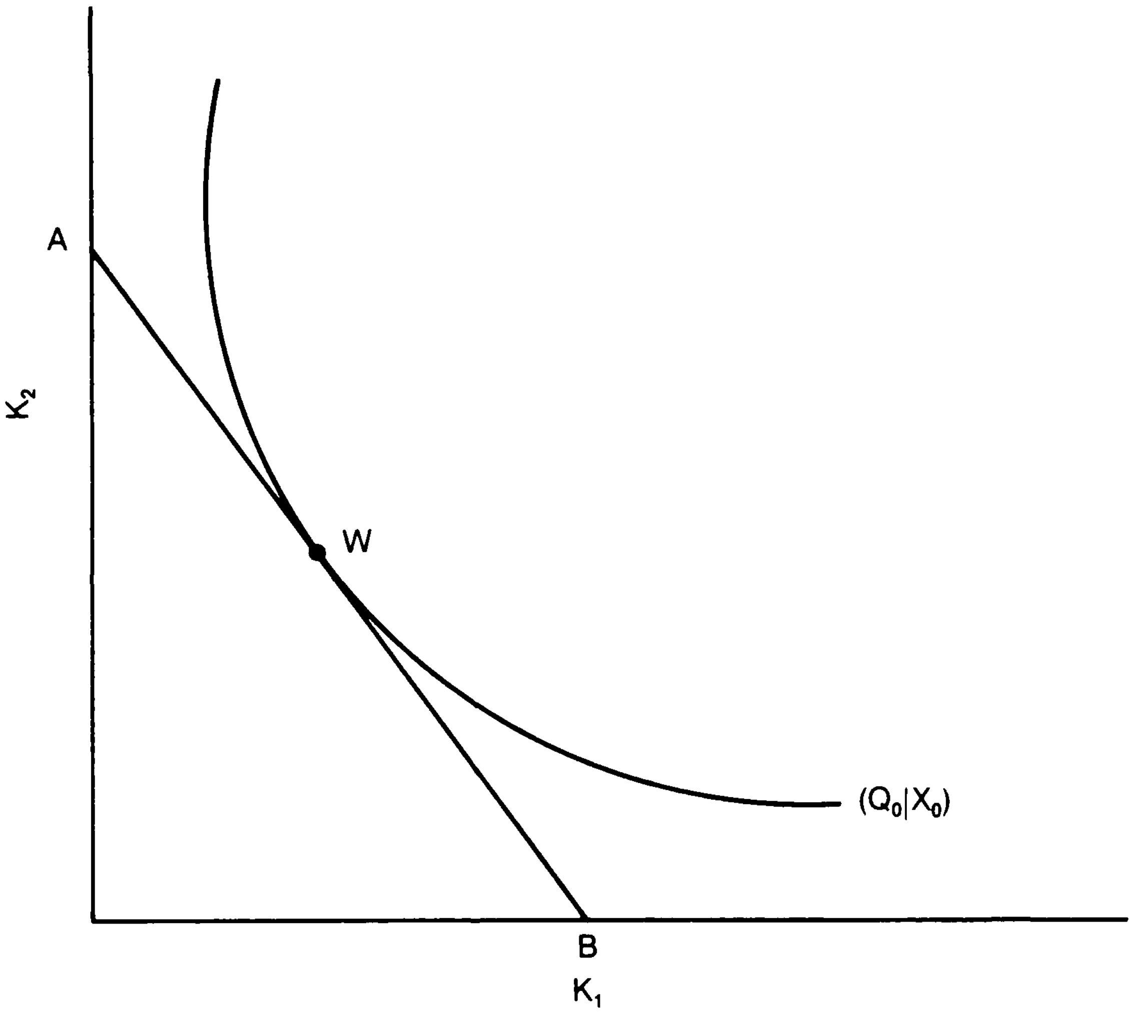


Figure 3-2
AN AGGREGATE CAPITAL INPUT

aggregation function was assumed. If AB is curved so that it exactly coincides with the shape of Q_0X_0 then there is no loss of information about the disaggregated inputs. One level of aggregate K produces one level of output; the production function is single-valued and monotonic.

Requiring the aggregation rule to coincide with the isoquant is a very restrictive constraint. The alternative to this constraint is to lose the results of the neoclassical production model which underlie the lock rehabilitation model.

The aggregation function must be generalized to cover the situation where the levels of output and the aggregate input are not constant. Figure 3-3 shows the case where a unique isoquant has been replaced by an isoquant map. Output varies but X is held constant. The isoquants show three levels of output for a given level of X but the labels on the isoquants need not be unique. Any point on any isoquant could be consistent with an infinity of(Q,X) combinations. For example, K=A could produce Q_1, Q_2, or any Q if X is varied enough.

Equation (1) says K depends only on the disaggregated quantities of lock capital. Thus we can rewrite (2) as

(3) $Q=h(g(K_1,K_2),X)$

which is nothing but the requirement of weak separability.
This is the first important conclusion about the generalized aggregation function g: micro inputs, in this case K_1, K_2, must be weakly separable from all other inputs and outputs in order for an aggregate input to

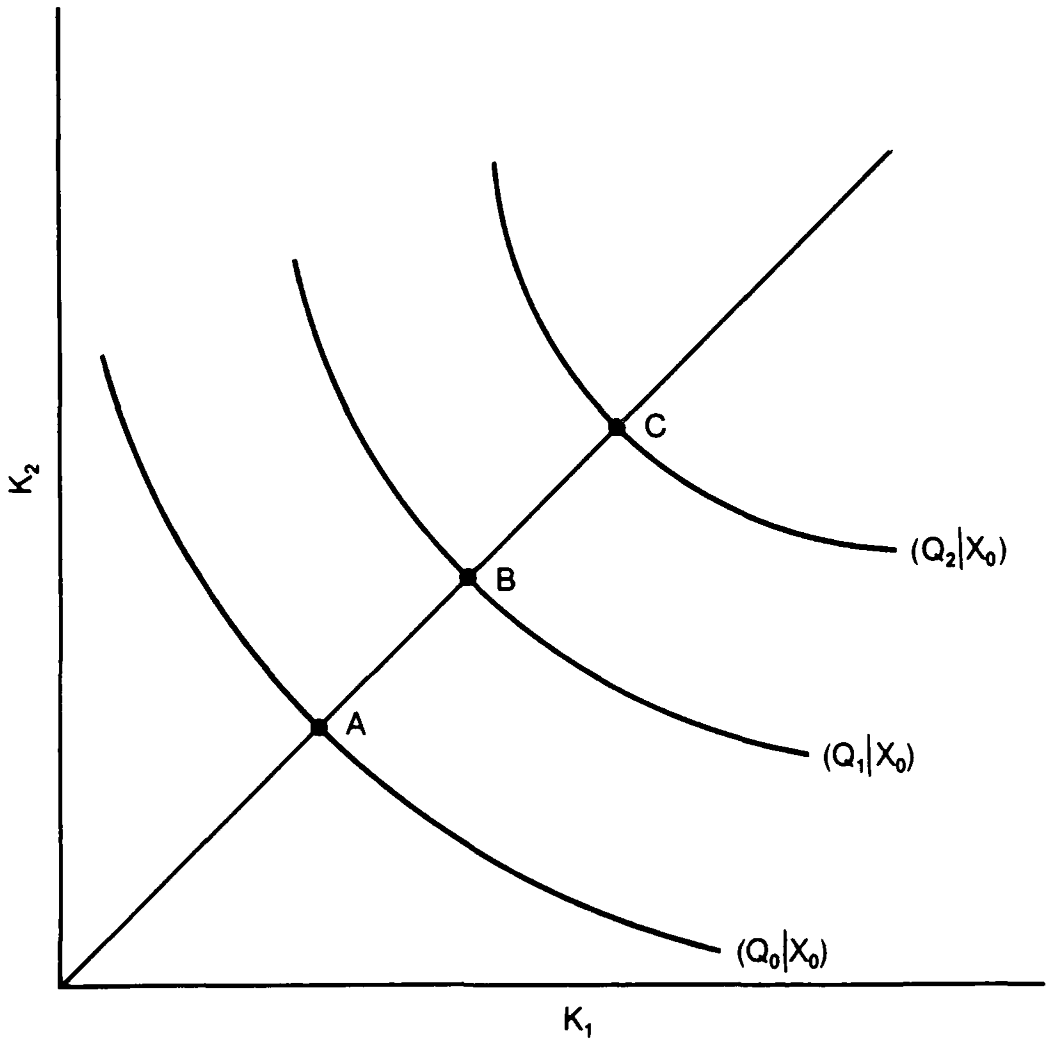


Figure 3-3
AGGREGATION AND THE ISOQUANT MAP

exist. The exception to this case is where the inputs are Hicks aggregates which is discussed later.

For a weakly separable aggregate, K, to exist is not enough to yield the desirable results of production theory. In order to measure K the aggregation function must also be homothetic. Monotonicity of the production function requires the aggregation function to coincide with the isoquant. Simple extension of the argument requires that with a single aggregation function the function must coincide with each isoquant. This can happen only if all the isoquants are identically shaped. Such an isoquant map occurs only with a homothetic function. With homotheticity the ray in Figure 3-3 cuts the isoquants at A, B, C where their slopes are equal. Homotheticity assures a linear expansion path.

A weakness of the model is that the aggregation function must coincide with each isoquant. If isoquants vary from one technology to another then consistent aggregation of capital would apparently have to be done separately. An aggregation function must be bent to each set of isoquants. To use a variable K for any lock with potentially differing technologies each lock i must have a production function

$$(4) \qquad Q_i = f_i(g(K_1, K_2), X)$$

where f_i is not to be confused with the f of equation (1). We first aggregated over inputs (analogous to aggregating over commodities in consumer theory) and now must aggregate over production functions (analogous to aggregating over consumers).

Aggregation over locks can be considered for two locks where K_1, K_2 and X are fixed in quantity and Q_1 and Q_2 are the respective outputs. Then we want an aggregate technology of the form:

(5) $Q=H(Q_1,Q_2)=f(K_1,K_2,X)$, or

(6) $Q=H(Q_1,Q_2)=F(K,X)$

Underlying the aggregate technologies in (5) and (6) is a disaggregated technology that can be characterized by the function

(7) $G(Q_1,Q_2,K_1,K_2,X)=0$

To move from (7) to (5) we must severely constrain the technologies of the two locks so that the isoquant maps are identical in every respect except labeling which may or may not differ. In (5) capital of different types has not been aggregated but isoquants are still stringently constrained. Moving to (6) and aggregating micro capital increases the constraints even more.

The simple expedient of estimating lock capital as a scalar rather than vector-valued variable imposes what is most probably an unrealistic set of constraints on the technologies of the waterway sector. Though the prospects of meeting the constraints of weak separability and homotheticity are in reality slim, limitations imposed by the availability of data and the need to use production theory results lead to acceptance of these stringent conditions of aggregation as maintained hypotheses. Empirical tests of these hypotheses will remain the subject of future research.

Hicks (1936) developed an alternative argument that provides for aggregation of quantities without imposing the rigid conditions observed above. The composite commodity theorem asserts that if a group of prices move together then the corresponding group of inputs can be treated as a single input. Staying with the lock capital input example say there are three inputs in the production function, K_1, K_2 and X with prices P_1, P_2 and P_x where

$$(8) \quad P_1 = wP_{01}, \; P_2 = wP_{02}$$

define prices as ratios of the zero-subscripted base prices. The ratio P_1/P_2 remains fixed at P_{01}/P_{02} but w varies over time. Thus w acts as the price for the aggregate input K. The quantity K is defined by weighting the K_1 and K_2 by the base period prices. The associated cost function is written as:

$$(9) \quad C^*(Y, P_x, w) = C(Y, P_x, wP_{01}, wP_{02})$$

Shepard's lemma yields:

$$(10) \quad fC^*/\partial w = (\partial C/\partial P_1)(\partial P_1/\partial w) + (\partial C/\partial P_2)(\partial P_2/\partial w) = P_{01}K_1 + P_{02}K_2$$

This confirms that input choices over K_1, K_2 and X lead to the same choices as those defined over the aggregate quantity, $P_{01}K_1 + P_{02}K_2$, where P_{01} and P_{02} serve as weights.

Most of the types of lock capital which could conceivably be combined in an aggregate index of capital are clearly close compliments or substitutes. It may not strain credulity to expect these prices of inputs to move very near in parallel. An analysis of construction costs undertaken by the Engineering News Record in March 1985 indicates that considerable divergence in relative prices has occurred at different points in time. Standing back from the data and looking at movement of relative prices of interest in this analysis over this century the reasonableness of an assumption like that in (8) is ambiguous.

Estimation of economic relationships and solution of the rehabilitation problem requires aggregation of lock capital so it can be quantified. Assuming homotheticity and weak separability of the aggregation function permits usage of production theory results developed for the individual firm to be used for the industry. The cost of these assumptions is to impose constraints that are not totally realistic on the analysis.

HOMOGENEOUS CAPITAL

It makes sense to aggregate into one homogeneous type of capital. Consider the case where all capital goods are constructed of homogeneous technical units much like the blocks children play with. These could be Swan's Meccano sets (1956) or Samuelson's "jelly capital" (1962). When capital goods can be assembled and disassembled costlessly the real aggregate quantity of capital is the total number of Meccano sets it contains.

Following Usher's model (1980), if there are n distinct types of capital goods and each type of capital good, i, consists of P_{ti} blocks per unit with K_{ti} units of the i type capital good in the economy in the year t, the total capital stock K in the year t can be unambiguously measured according to the formula

$$(11) \quad K_t = P_{01}K_{t1} + P_{02}K_{t2} + \ldots + P_{0n}K_{tn}$$

The first subscript t represents time, the second represents the i-th capital good. P_{ti} has t equal to an arbitrary constant, 0, to indicate that the number of Meccano sets per capital type does not change over time. This is equivalent to an assumption of constant technology.

Samuelson has shown that a one-to-one correspondence between such homogenous capital stylizations and "real" world heterogeneous physical capital models can be obtained via the factor-price frontier if the right brand of "jelly" is used.

Changes in the nature of capital goods themselves and variation in the patterns of depreciation of capital goods have been assumed away in (11). Physical capital is so diverse as to defy enumeration in all but the simplest production settings. Despite these difficulties capital is most frequently treated as a homogeneous quantity.

VOLUME CAPITAL OR VALUE CAPITAL?

What is sought is a scalar value measure of the capital stock's ability to produce a flow of services.

Measures of real lock capital and lock investment (rehabilitation) can be approached in two basic ways summarized by Hicks (1974). Materialists consider real capital as a stock of physical goods or volume capital. Fundists consider real capital a fund or flow of economic values or value capital. Real capital measured by these two methods does not measure the same thing the way ounces and pounds both measure weight.

Less popular variations of these two approaches can be found in the literature. Jerome (1934) suggests using physical dimensions such as volume, weight, size, number of machines, etc. Numerous others have suggested using a summation of physical inputs which enter into the capital stock components, e. g., embodied labor. Another method is to quantify the current operating input requirements of the capital stock in some common measure such as energy consumption or horsepower rating. Beach (1938) has suggested a method which requires construction of an index of fixed assets expressed as years of service still available.

One of the most popular value measures of capital is the deflated cost of capital stock, the method used in this analysis. The chief rival to this method in popularity of use is to estimate the value of capital from the value of all of the present capital stock's future net product at current or estimated prices deflated by a proper index.

As a practical matter lock capital cannot be measured as a vector-valued volume variable. It is too complex and varied to be successfully characterized by a few types of physical capital. Even if lock capital could be so characterized common units of measurement are not available.

As a result lock capital will be estimated as a scalar measure of the value of the stock of capital.

SUPPLY VALUE VS. DEMAND VALUE

The next choice in quantifying the value measure of capital involves the supply value (cost) vs. demand value (value) controversy. This controversy in essence turns on the point that capital can be measured as the cost of the capital, i. e., its historic cost deflated or as the value of the discounted future earnings of the capital.

To understand the controversy it is convenient to consider lock capital as two sums of money. One is the amount of money it costs to construct a lock; the other is the discounted future stream of benefits which accrues to the lock capital. The two values never coexist in time. Many things can happen to make the cost of capital diverge from its value.

In a world of perfect information and certainty these two sums of money would identically measure the marginal value of capital. A problem arises because capital lasts longer than one period. There is time between the investment of money and receiving the benefits. During this time many things can happen to change the value of the two theoretically identical prices. Interest rates, technology, demand for the capital's services, profits, etc. all can change. For lock capital the real price of rail or other transportation modes could change. Natural disasters or new transportation routes may render the capital worthless. In an uncertain world the measure of capital based on supply price will equal the value of capital based on expected future earnings (demand price) only by accident.

To estimate the supply price we look at costs of producing the lock. Actual costs are of historical interest only; the purchasing power of money has changed enough to render them useless. Current replacement costs are little more than academic exercises; their generation presupposing the same lock would be built again. Deflated costs, or costs in real dollars are most useful but they require a price index.

Estimates of the demand price of lock capital present even larger obstacles. There are no markets for locks, new or used, so market price information does not exist. Estimating the present worth of the accumulated sum of discounted future earnings is also impossible. In this analysis an estimate of the value of capital is needed to estimate future benefit streams. To use current estimates of future benefit streams to estimate the value of capital which is necessary to estimate project benefits is circular reasoning.

Theoretical arguments suggest that demand price is the relevant value because all costs are sunk and it best represents the ability of capital to produce a flow of services into the future. Unfortunately, estimation of demand prices is not feasible; the necessary data do not exist. Supply price is the best available basis for the estimate of the value of lock capital and it is used in this analysis because it can be estimated.

Lest supply price be sold short as the value measure the intended use of the capital variable must be born in mind. First, rehabilitation effort or additions to lock capital will be measured in terms of supply price. This is entirely reasonable and is a far more dependable estimate than demand value. Second, an estimate of the magnitude of existing lock capital that makes sense in a production function context is needed. Given the available choices, the real cost of the depreciated lock capital in existence makes more sense as an index of lock capital in a cross sectional analysis than any other demand or supply value.

Ignoring the valuation of capital for tax or accounting purposes as irrelevant in this problem there are two ways to estimate the supply value of capital. One is by direct measurement, the other by the perpetual inventory approach.

Direct measurement of the cost of capital through detailed surveys of the cost of capital goods in place is seldom used because of the lack of reliable data on prices. The perpetual inventory method of valuing capital builds up a time series of capital stock step-by-step using prices of capital goods and dollar values of investment.

Not to be overlooked in this discussion is the fact that different definitions of capital can lead to different empirical results and conclusions. For example, two locks of identical design and construction would have identical amounts of capital if deterioration is ignored and we use a physical measure. These same two capital stocks when measured by demand value could have widely differing values. The value of capital stock for a lock which is abandoned would be zero. The supply value of the capital stock at this lock when measured by the perpetual inventory method may well be significantly higher than zero. In practice the issue of which method to use to quantify capital has trade-offs but no right answer.

An important point needs to be made considering the quantification of lock capital and rehabilitation effort. Rehabilitation efforts are limited in scope and very specific in effect. It may be clear that certain elements of a rehabilitation alternative will not contribute to the productivity of the existing lock. For example, if a significant amount of the cost must be spent for environmental mitigation measures or for land easements to rehabilitate the project it is obvious that these measures will not contribute to the productivity of the lock.

The arguments, estimation and analysis presented in this paper should never be construed so as to take the place of common sense or to supercede a priori information which would improve the analysis. The rehabilitation and lock capital variables function as indices. If they can be improved through a priori information they should be. If elements of the construction costs of the original project or the rehabilitation can be identified as not contributing to the productivity of the lock these dollar amounts should be eliminated from the index. The method developed in this research cannot be substituted for careful thought. The type of adjustments which are appropriate can be determined only with a thorough understanding of the elements of specific rehabilitation alternatives and the construction history of the lock.

In summary, I argue that lock capital is best defined to be a scalar supply value measure based on deflated historical costs measured by the perpetual inventory method. This definition provides the best index of capital considering the available data and the intended use of the data.

THE PERPETUAL INVENTORY METHOD

The perpetual inventory method requires a time series of gross investment in current dollars, I_{ti}, where t refers to the year and i to the type of capital good; a time series of capital good prices, P_{ti}; and a rule linking values of new and old capital goods from which a time series of depreciation, D_{ti}, can be computed. Continuing with Usher's model for each type of physical capital good the increase in real capital in any year t is

$$(12) \quad K_{t+1i}-K_{ti}=(I_{ti}-D_{ti})/P_{ti}$$

and the value of each K_{ti} in equation (11) can be estimated as the value

$$(13) \quad K_{ti}=K_{0i}+\sum_{s=0}^{t-1} K_{(s+1)i}-K_{si}$$

K_t can be estimated by weighting the K_{ti} by the base period price of capital goods where P_{0i} in (11) now represents supply price rather than Meccano sets.

The perpetual inventory method suffers from two shortcomings that require particular notice. First, the method is very theoretical in that it never ties in to a real world inventory of physical capital. Capital stock in any year is the sum of the increments in every preceding year. There is no need for an actual inventory at time 0 or time T. The method does not depend on physical quantities at all; it relies on ratios of values and prices. Therefore any errors in estimating I, D, or P can compound throughout the time series.

The second major shortcoming of the method is that it always works as long as there are data on gross investment, depreciation and price indices. Given these data a time series of capital stock can be estimated no matter how long the period or how much technology or the nature of the good itself have changed. Their is no red light that goes off when the process has become absurd. A description of how the perpetual inventory method was applied to estimate lock capital follows.

DEFLATED COST OF LOCK CAPITAL

The Annual Reports of the Chief of Engineers on Civil Works Activities provides first cost of construction for most lock and dam projects. Investment in large public works projects like locks and dams is necessarily lumpy. After a large initial investment there is typically no further investment unless and until major rehabilitation is done. The gross investment pattern for a lock project that has not been rehabilitated is essentially defined by the historical first costs of construction and the period of construction.

Year-by-year schedules of lock construction expenditures are not available so the expenditure pattern is assumed to be evenly distributed over the construction period. Interest costs during construction are not included in the first costs. Normal operation and maintenance expenditures are not investment costs and are not included as part of the gross investment pattern.

There are several indices available for expressing the gross investment pattern in equivalent money units; the Engineering News Records' indices of construction and building costs, the Department of Commerce value of new construction index, and the Bureau of Reclamation's water resource project construction cost indices. A Bureau of Reclamation index for concrete dams based on actual bid prices for water resource projects is used because it is the best index available.

The index was used to reduce all first costs of construction to a 1984 price level. The real cost of lock capital in 1984 dollars is considered to be the best index of the magnitude of physical capital installed at various locations given the available data.

DEPRECIATION

Depreciation of capital is crucial to this analysis. It determines the existing and future levels of capital. These values are the basis for the estimation of the transit time model in Chapter 4 and the solution of the model in Chapter 2. The estimates of lock capital described above indicate that a project that cost $200 million dollars has about twice the capital of a project costing $100 million. If the first project was built in 1960 and the second in 1935 the relevant question is how much lock capital existed at each project in 1984. The answer to this question depends on the depreciation of capital.

DEPRECIATION PATTERN

There is a substantial literature on the theory and estimation of economic depreciation. Estimation techniques are divided into price and quantity approaches. Price approaches rely on age-price profiles based on data from used asset markets. Quantity approaches rely on useful lives and retirement patterns. Neither of these approaches can be supported by available data for locks.

The physical depreciation pattern for any capital asset is determined by the asset's useful life and its depreciation path. No one knows what the useful life of a lock and dam project is. The useful lives of these projects clearly exceed the arbitrary 50-year planning horizon adopted at the time of their construction but by how much?

Some Corps personnel regard these structures as virtually indestructible. This research is motivated by the concern of other Corps experts that locks are sufficiently deteriorated as to present a significant threat to the future reliability of the system. Estimating a single useful life for a complex array of capital assets is never going to be completely satisfactory. The need to quantify aggregate lock capital nonetheless requires a single useful life estimate.

A search of the literature on the useful lives of assets reflects the lack of data for assets of this type. Bulletin F issued by the Internal Revenue Service in 1942 and the "bible" of useful life estimates estimates the useful of an earthen, concrete or masonry dam to be 150 years. The Bureau of Economic Analysis (Young and Musgrave 1980) estimates the life of water structures as 60 years. Corps experts variously estimate the useful life from little more than 50 years to "a very long time". Locks and dams are assumed to have a 150-year useful life in this analysis. A 100-year life is also considered to test the sensitivity of results to the assumed useful life. Long lives are assumed because experience has shown them to be more reasonable than 50 or 60-year lives.

In the absence of price data for used lock and dam assets the estimation of the depreciation function depends on physical deterioration patterns. The four basic patterns for depreciation of a capital asset are shown in Figure 3-4. Hulten and Wykoff (1981) have defined an efficiency index of a used asset as the marginal rate of substitution in production between the used asset and a new asset. First is the one-horse shay path. This path is typically illustrated by a light bulb which burns at full intensity until it burns out. There is no observable physical deterioration and productivity of the asset is undiminished until the asset dies. Next in simplicity is the straight line depreciation path. This is estimated by dividing the asset value or an efficiency index of one by the useful life of the asset. Geometric decay of asset efficiency is one of the most common representations of a depreciation path. Such functions are of the general form

(14) $D=1/(1-d)^t$

where D is asset value or an efficiency index, d is the rate of decline and t is an index of time. A less frequently observed efficiency decline function is concave to the origin and in general is given by

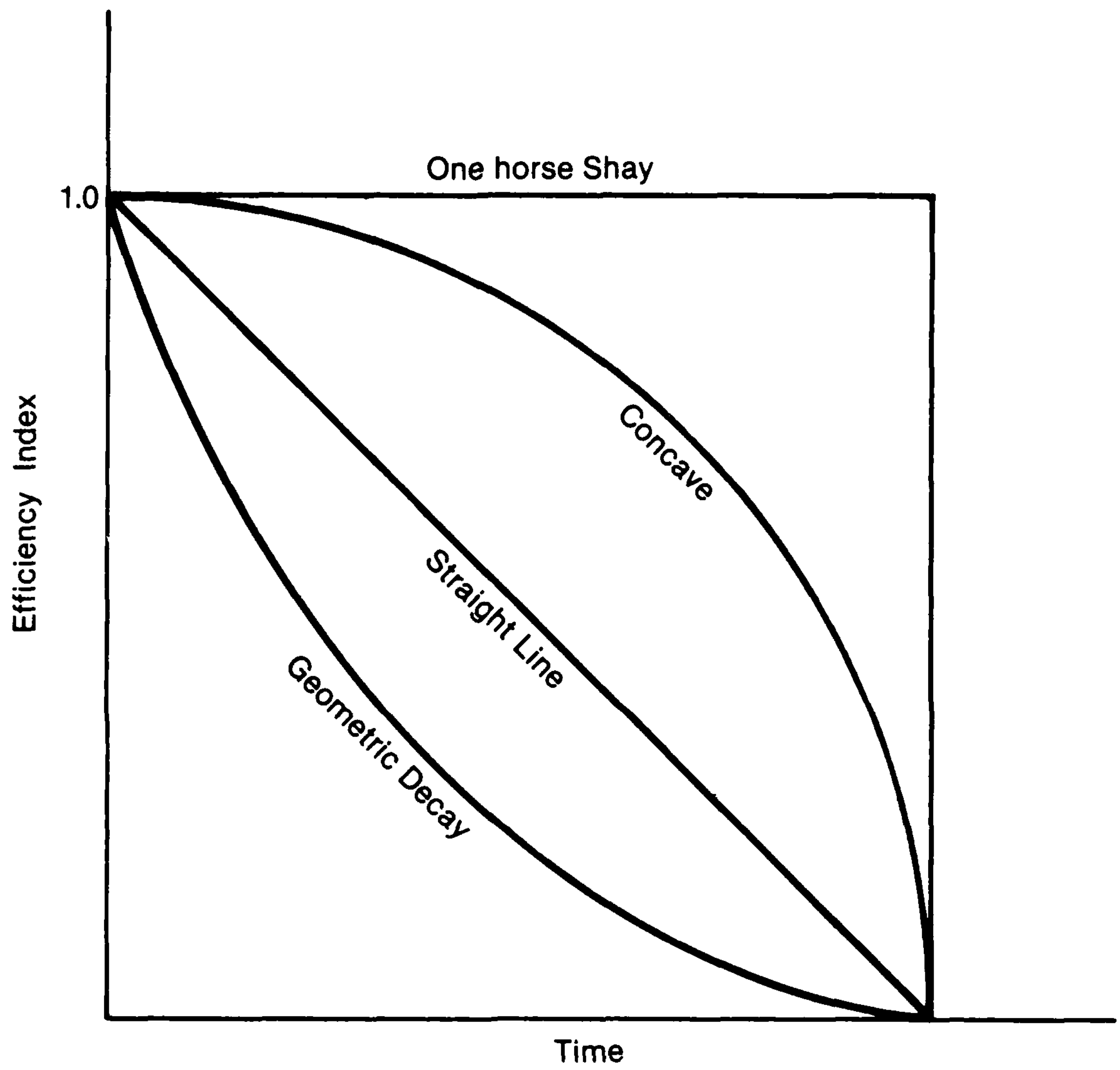


Figure 3-4
CAPITAL STOCK EFFICIENCY PROFILES

(15) δ=(asset life-age)/(asset life-ξ*age), $0 \leq age \leq asset\ life,\ 0 \leq \xi \leq 1$
=0, $age \geq asset\ life$

with δ the efficiency index at a given asset age and asset life and ξ a parameter. Considering the possible values for an asset's useful life, the form of the depreciation function and the specific rate of depreciation the number of possible depreciation paths is unlimited.

The monolithic nature of the lock capital asset persistently suggests a dimension of durability if not indestructibility. A concave to the origin decline in efficiency function such as 4 in Figure 3-4 best reflects this monolithic nature. Assets with such a depreciation function are characterized as losing relatively little efficiency during the early years of service life. Efficiency declines at an increasing rate over the life of the asset. Personnel of the Corps' Waterways Experiment Station agreed that this is a reasonable depreciation path for a lock. This function also reflects the concern which underlies the surge of interest in lock rehabilitation. No one knows if or when efficiency will take the precipitous plunge shown in Figure 3-4, but the possibility that it could happen causes real concern about the future reliability of the system.

A concave to the origin loss-of-efficiency function best represents the depreciation path of lock capital. A commonly accepted estimate of the depreciation rate and the best estimate of B in this analysis is twice the reciprocal of the useful life.

LOCK CAPITAL

Lock capital must be aggregated to be measured. Aggregate capital must be weakly separable from other inputs and outputs and the production function must be homothetic to yield the results of economic theory which allow solution of the model presented in the previous chapter. Alternatively the prices of the micro inputs must move proportionately over time. Costs of construction were obtained for the 78 locks which make up the data sample assuming a useful life of 150 years and a concave to the origin depreciation function. The rate of depreciation is assumed to be 1/75 yielding a $\xi = .9866$. Using these assumptions the quantity of lock capital can be estimated for each lock from the time of construction to the present. All price data in this analysis are in 1984 dollars.

To test the sensitivity of estimation and model solution results to the definition of lock capital several other estimates of lock capital were generated. Appendix 2 contains estimates of the 1984 quantities of capital existing at the sample locks based on 11 different sets of depreciation assumptions.

CHAPTER 4

ESTIMATION

INTRODUCTION

The cost to a shipper of using a lock is directly related to the time it takes to transit the lock. Transit time is composed of time spent waiting in queue, time delayed because of stalls and the time it takes to move through the lock.

The primary hypothesis of this research is that there is a causal relationship between the amount of lock capital and the total time it takes to transit a lock. Specifically an increase in lock capital, ceteris paribus, results in a shorter transit time. The hypothesis is

(1) $\partial \text{transit time} / \partial \text{lock capital} \leq 0$

This hypothesis stems from a model that has been specified and estimated. The method and results of this estimation are the subject of this chapter.

LOCK CAPITAL AND TRANSIT TIME

Rehabilitation increases the amount of capital available at a lock. The relationship of interest in this analysis is the marginal product of capital in the production of lock output measured as total transit time per tow.

The model described below is not a production function in the typical sense. As a matter of semantics it may better be described as a process function. The distinction between the two is that with a process function there is only one way of producing an output while a production function represents many ways of producing an output.

Economic theory provides the basis for the hypothesis in equation (1). The arguments presented in the model which follows do not conform to the typical definitions of inputs and outputs and the differences become distracting when couched in the neoclassical language. Presenting the relationship as a process function frees us from this difficulty while allowing us to retain the essential elements of production theory.

The purpose of the model is to show the effect of lock capital on a tow's transit time. At a basic level the process is simple. A tow arrives at a lock and it takes x_1 minutes to get through the lock. Part of that time may be spent waiting in queue or delayed by a stall and the rest moving through the lock. Lock capital in part determines the mean speed and efficiency with which a tow can be processed through the lock. As the lock deteriorates over time it functions less efficiently and mean transit time increases. Rehabilitation restores the productive efficiency of the lock and decreases mean transit time.

Lock capital is the factor of interest but it is not the only factor affecting transit time. The configuration and characteristics of the tow, navigation conditions, traffic levels, experience of lock operators and tow personnel, etc. affect lock transit time via the systematic relationship described below.

Transit time is not expressed as the identical sum of waiting time, stall delay time and service time because stall delay time could not be reliably estimated with the available data, as explained in Appendix 4. Thus expected total lock transit time is initially expressed as:

(2) Transit time=f(service time, queue length, occurrence of stall, lock characteristics, tow characteristics, other factors)

Lock capital is not shown as a direct argument. It enters the transit time function indirectly as an argument for service time and queue length. Demand for lock services enters indirectly as an exogenous argument.

Service time, x_1, is expressed as:

(3) Service time=x_1(lock capital, navigation conditions, tow characteristics, lock characteristics, operating conditions)

Operating characteristics include traffic levels, experience of personnel, etc.

Expected queue length, x_2, is described by:

(4) Length of queue=x_2(service time, demand for lockages, inter-arrival period, annual number of stalls, annual downtime due to lock-related stalls, operation characteristics, lock characteristics)

The expected length of queue is not directly affected by the amount of lock capital. Lock capital enters as an argument for queue size through its effect on service time.

The cumulative effect of lock capital on total transit time is realized through its direct effect on service time and its indirect effect on queue size. From the notation in equations (2)-(4) and suppressing arguments not affected by lock capital, transit time can be reexpressed as:

(2a) $\text{Transit time} = f(x_1, x_2(x_1))$

The cumulative effect of lock capital (K) is given by:

(5) $\partial\text{Transit time}/\partial\text{Lock capital} = (\partial f/\partial x_1)(\partial x_1/\partial K) + (\partial f/\partial x_2)(\partial x_2/\partial x_1)(\partial x_1/\partial K)$

The system is dynamic because as a result of depreciation there is less capital stock available each year. The initial level of lock capital and its mortality distribution provide a schedule of lock capital over time. This time path for lock capital, in turn produces a time path for service time, queue length, and transit time. After rehabilitation the initial level of lock capital is higher and a new and higher schedule of lock capital over time results along with new endogenous variable paths. Figure 4-1 illustrates this effect for a hypothetical 1990 completion of a $12.4 million rehabilitation of Lock and Dam 13 on the Mississippi River.

The process function expressing transit time as a function of lock capital estimated in this analysis is most nearly an average ex ante micro process function as defined by Johansen (1972).

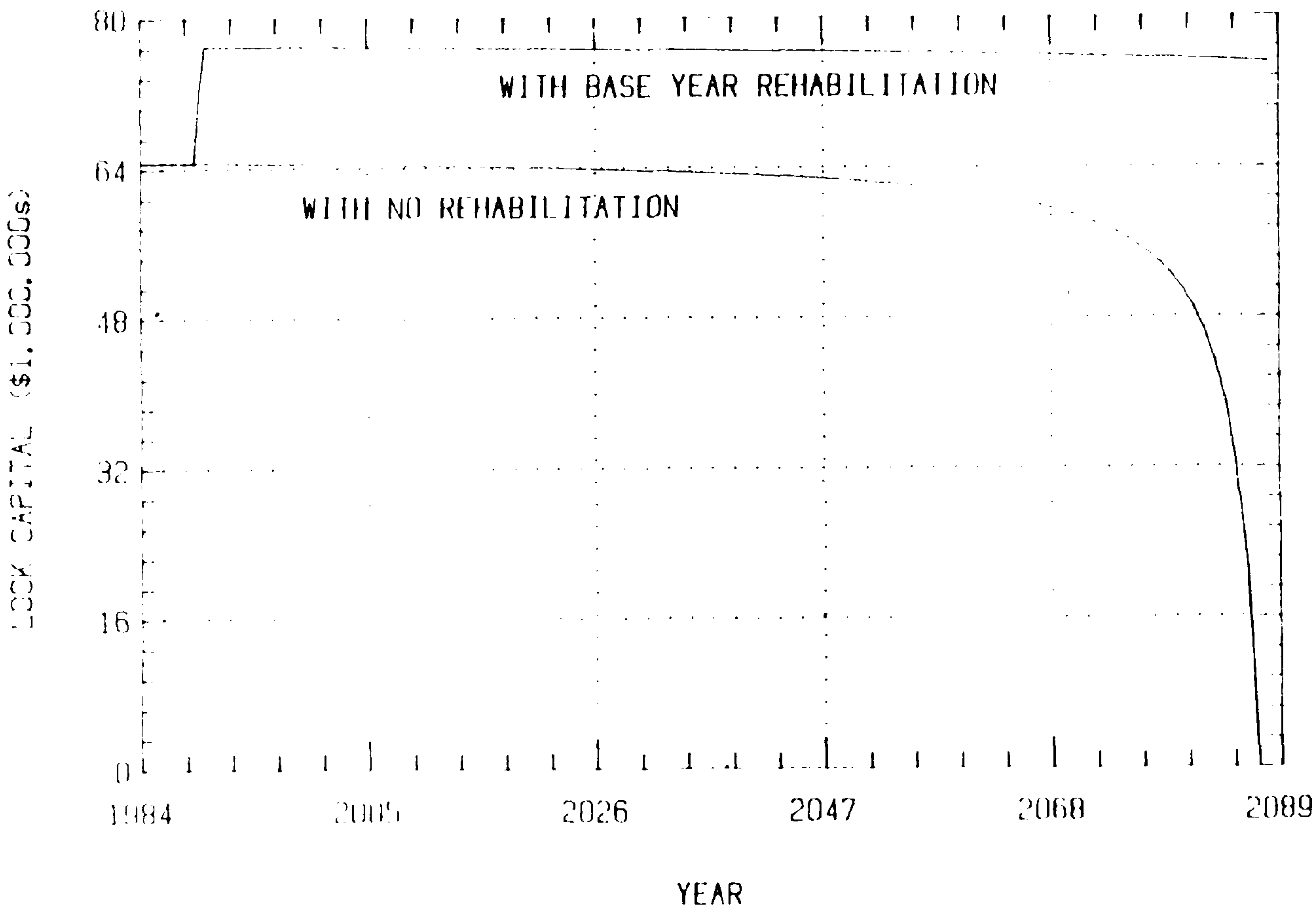


FIGURE 4-1: PLOT OF LOCK CAPITAL VS TIME W/ BASE YEAR REHAB & W/ NO REHAB

DEMAND FOR LOCKAGES AS AN EXOGENOUS VARIABLE

Demand for lock services, measured as the number of commercial tows per year (L in the model of Chapter 2), is treated as an exogenous variable in this analysis and in the estimation to follow. Transit time is a proxy for the price of a lockage, but demand for lockages at a specific lock is in no way determined by the system of equations presented above. If demand for lockages at a specific lock is treated as exogenous but in fact is not one of two problems can arise. First, the parameter estimates could be wrong. For example, estimation of a simultaneous system of equations by single equation estimation techniques can lead to estimate errors. Second, the parameter estimates may be right but the magnitude of benefits could be wrong if the response of demand to price change is not accounted for.

To understand why demand is considered exogenous the demand for commodity transportation must be viewed at several levels as provided in the following hierarchy of demand for a commodity to be transported:

(6a) S_i-quantity shipped from region i

(6b) D_j-quantity shipped to region j

(7) Q_{ij}-quantity shipped from region i to region j

(8) Q_{ijm}-Q_{ij} shipped by mode m

(9) Q_{ijmr}-Q_{ijm} shipped via route r

(10) Q_{ijmrp}- Q_{ijmr} shipped over element p of route r

The hierarchical structure can be exploited by developing a chain of sequential demand models where each demand is a function of the preceding higher level of demand. The model illustrates the point that supply and demand of certain commodities are linked to the demand for lockages at a specific lock while at the same time indicating that the levels of the hierarchy insulate the economic choices at one level from those at another level. The derived demand for lockages is sufficiently removed from the demand for a commodity or the demand for waterway transportation as to be reasonably considered exogenous.

Freight transport models are often characterized by long term shipping arrangements which combine into an inertia effect which limits the response of shippers to market forces. The waterway industry is subject to such an effect because of the following factors:

* Long-term contracts between shippers and carriers remove goods from intermodal competition for the duration of the contract.
* Investment in long-term capital designed to interface with a single transportation mode, e.g., loading docks and port facilities.
* Shippers often own their transport fleets.
* Shippers sometime lack knowledge of alternative transportation services resulting in shipper rigidity.
* Legislative and regulatory control and taxes in other modes often encourage shippers to remain within their familiar mode.
* The Federal government pays the short run marginal costs of

operating the waterway so shippers are able to absorb short run increases in costs.

The relative advantages and disadvantages of the various modes will dampen the demand response for relatively minor changes and fluctuations in cost.

In addition to the above arguments substitution possibilities can become limited and ultimately eliminated as choices are made and we move down the demand hierarchy. Assume that at the point of modal choice we have perfect substitution possibilities as shown in Figure 4-2a. Conceptually as we move to production choices at subsequent levels of the hierarchy we have imperfect substitution possibilities as shown in Figure 4-2b. When we reach the lock specific level of derived demand we essentially have a recipe for production; one lockage, one tow, one operator, etc. The production possibilities underlying the lockage process are characterized by a Leontief technology as shown in Figure 4-2c and can be characterized by the function:

$$(11) \quad Y=\min(\alpha_i x_i, \ldots, \alpha_n x_n)$$

Costs associated with this technology are:

$$(12) \quad C(W,Y)=WX=\Sigma w_i x_i=Y\Sigma(w_i/\alpha_i)$$

Applying Shepherd's lemma shows demand for lockages is a constant. Exogenous demand is reasonable for this fixed inputs model with negligible price changes.

(a)

(b)

(c)

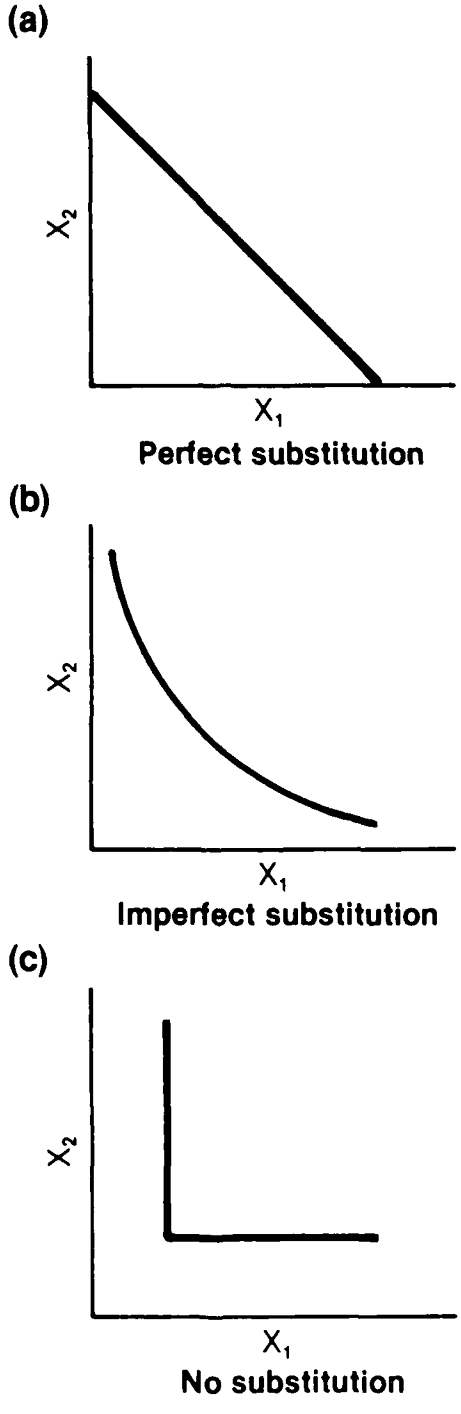


Figure 4-2
SUBSTITUTION POSSIBILITIES WITH HIERARCHICAL DEMAND

The insulation of the demand for lockages from choices made higher in the hierarchy of demand is supported by the following example based on some average data and empirical results of this and the next chapter. In 1983 the average waterway movement travelled 437 miles at average speeds ranging from 2.27 mph to 6.38 mph depending on the waterway and the direction of travel. At these speeds the average trip takes from 68 to 193 hours disregarding time in port. Several locks will be passed through on an average trip.

Corps experts estimated the time saved by rehabilitating a single lock would be an insignificant part of the total shipping time. Empirical results presented in the next chapter bear this out showing a 2 minute mean time saving per tow over a 50-year planning horizon. This represents a 0.05 or 0.02 percent savings of time underway. For convenience assume cost decrease by the same amount. (They will actually decrease by less than time does because the example does not include any port or other costs.) If waterway transport costs are 10 percent of the delivered cost of a commodity with unitary demand elasticity then rehabilitation results in a price decline in the range of 0.002 to 0.005 percent. With cost changes of this magnitude it is reasonable to assume no resulting change in commodity supply and demand or waterway transportation demand. Waterway costs routinely vary so much from trip to trip because of wide and often stochastic variations in input requirements that such a small cost decrease would go unnoticed. Relatively significant impacts at one level of the hierarchy can become significantly dampened and ultimately negligible at higher levels in the hierarchy where the choices that determine demand in lower levels of the hierarchy are made. A change in lockage costs at a specific lock may be relatively large at the $Q_{ijm_{rp}}$ level but negligible at the levels where production (S_j) and modal choice (Q_{ijm}) decisions are made.

HYPOTHESIZED SIGNS OF PARAMETERS

The a priori expectations about the signs of parameters in the above functions are the basis for the evaluation of the estimation results. Production theory suggests that the effect of increasing capital input in the relevant range of production should be to increase output. Thus we expect

(13) $\partial OUTPUT/\partial INPUT \geq 0$

The output variable, total transit time, is measured in minutes per tow. Its inverse, tows per minute, may be a more traditional measure of output but the model is formulated to correspond to the traditional variables used in navigation benefit estimation. Thus, output is consistently expressed in terms of time per unit rather than the inverse.

Using a traditional measure of output like tows per minute we expect an increase in lock capital to increase the number of tows per minute. The increase results from the fact that the number of minutes required to process a tow through the lock is decreased. If the number of tows per minute increases, its inverse decreases. The expected result, entirely consistent with economic theory, is:

(14) ∂total transit time/∂lock capital ≤ 0

As noted above lock capital does not enter transit time as a direct argument. The hypothesis in (13) can only be tested after estimation of the entire model outlined in (2)-(4) above.

The expected effect of lock capital on service time consistent with the above discussion is:

(15) ∂service time/∂lock capital ≤ 0

In turn an increase in service time will increase transit time or:

(16) ∂total transit time/∂service time ≥ 0

Equations (15) and (16) together lead to the expected negative relationship of (14). Because transit time is the sum of service time, time in queue and stall time, a one minute increase/decrease of service time is expected to increase/decrease transit time by one minute. Thus (15) can be restated definitively as:

(15a) ∂total transit time/∂service time = 1

and the effect of lock capital on service time is expected to pass through unchanged to transit time. This is not the entire effect, however.

Capital also enters transit time as an indirect argument through queue length. Queuing theory and common sense lead us to expect:

(17) ∂queue length/∂service time ≥ 0, and

(18) ∂transit time/∂queue length ≥ 0

Equations (15), (17) and (18) lead to :

(19) (∂transit time/∂queue length)(∂queue length/∂service time)(∂service time/∂lock capital) ≤ 0

The results of (15) and (19) sign the terms of equation (5).

THE NATURE OF THE SYSTEM OF EQUATIONS

The estimation model provides a formal framework for a stimulus-response interpretation of the effects of lock capital on the endogenous variables of the system. The three endogenous variables in the system are: 1) total transit time (TIME), 2) length of queue (QUE), and 3) service time (SERVICE). The system of equations is linear in parameters and can be expressed as:

(20) $\beta y + \Gamma z = u$

where y is the vector of endogenous variables; z, a vector of K exogenous variables; β and Γ are the corresponding parameter vectors; and u is a vector of N random disturbances.

The exact part of the system has the following recursive character:

$$(21)\quad \begin{aligned} \beta_{11}TIME+\beta_{12}QUE+\beta_{13}SERVICE+\Sigma a_{1K}z_K &= u_1 \\ \beta_{22}QUE+\beta_{23}SERVICE+\Sigma a_{2K}z_K &= u_2 \\ \beta_{33}SERVICE+\Sigma a_{3K}z_K &= u_3 \end{aligned}$$

The sequence of events in the system is one-way-directed upward. Service time is a function of lock capital and other exogenous variables. Queue size depends on the time it takes to service a tow, the arrival rate of tows and other exogenous variables. Service time, queue size and transit time are sequential rather than interdependent relationships.

Total transit time begins when a tow arrives at a lock and ends when the tow exits the lock. By definition it consists of service time plus waiting time. Waiting time consists of time in queue and time waiting because of stalls. By holding all exogenous variables constant except lock capital, transit time can be expressed as a function of lock capital through simple substitution. Computation of the marginal product for lock capital is then possible.

FUNCTIONAL FORM OF THE MODEL

Theory sometimes indicates the exact number of equations in a model or the precise mathematical form of the relationships. Queuing theory develops parametric relationships for waiting time, service time, queue length, etc. These relationships could have been used if the assumptions of Poisson distributed arrival of tows and negative exponential distribution of their servicing which underlie queuing theory held. They did not. Hypothesis tests of these assumptions are described in Appendix 3.

Known process functions, i.e., functional expressions of engineering or production relationships, were investigated. No usable relationships were found. Little of the processes regarding lock performance have been or can be reduced to equation form.

In the absence of a priori theoretical structures and mathematical forms for the relationships other methods were used to estimate them. The production literature was reviewed and the Cobb-Douglas, quadratic, CES, linear, translog and generalized Leontief forms were tested.

Many of the independent variables of interest take an observed value of zero. Some of these variables are dummy variables, others are not. Models like the Cobb-Douglas and translog requiring log transformations of these zero values for estimation presented something of a problem in analysis and were not considered further. A linear model was considered insufficient to yield use of desired theoretical results because it imposes a constant marginal product on capital. Allowing for substitute and complement relationships among exogenous variables was considered essential. The model that best avoids the problems of log transformations and linearity while allowing for interaction terms is the generalized leontief. Diewert introduced this form in 1971 and it is given by:

(22) $$G=\sum_{j}\sum_{k} a_{jk}(x_j)^{.5}(xk)^{.5}$$

The nature of the lockage process and the data have resulted in the coefficients of most interaction terms being set equal to zero.

DATA FOR ESTIMATION OF THE MODEL

Appendix 1 provides details on the data base used in this analysis. Each observation consists of lockage-specific data, i.e., variables whose values change with each individual lockage, and lock-specific data that consist of variables whose values are constant for all lockages at a given lock but that vary from lock to lock. To overcome the logistic problems created by the large data base an approximate 5 percent random sample of 330,436 observations from a data set of 78 locks was selected for final model estimation. To avoid pre-test bias problems two data samples were drawn independently, a large one of 15,104 records for final estimation of the model and a 3,783 record sample for model building experimentation.

The final estimation sample was constructed from three types of observations. They were: records not affected by lock stalls, records affected by lock-related stalls, and records affected by other types of stalls. In order to preserve information in the sample about these three types of lockage records a stratified sample was selected.

The 5 percent sample size is based on the sample size required to estimate the population means of queue length, transit and service times with a bound on the error of about 2 minutes on the time values and well under ±2.5% on queue length. The determination of the required sample was determined by the formula:

(23) $n=(N\sigma^2)/((N-1)D+\sigma^2)$, where

(24) $D=B^2/4$

and B is the bound on the error, N is the population size and σ^2 is the population variance.

The actual population parameters were not computed for the three variables. Estimates of σ^2 were obtained from the variance of individual lock populations. A 5 percent sample was greater than the required sample size for the error bounds specified for each of the three variables. An arbitrarily high round number of 5 percent was chosen as the sample size to insure a sample of adequate size with acceptable error bounds for the variables used in the estimation.

CHOICE OF ECONOMETRIC TECHNIQUE

For a recursive system of equations estimation is a simple matter of choosing an appropriate single-equation estimation technique. Ordinary Least Squares (OLS) is considered the most appropriate technique for estimating the transit time and service time. However, the endogenous variable queue length is often observed taking the limiting value zero and OLS is not appropriate.

Tobin in his seminal 1958 article on limited dependent variables argued that when a concentration of observations at the limiting value of a dependent variable occurs the explanatory variables can be expected to influence both the probability of observing a response that takes on the limiting value and the size of the non-limit responses. This dual effect must be taken into account when estimating the relationship of a limited variable to other variables and in hypothesis testing.

OLS assumes that the error term is a random variable distributed normally with zero mean and constant variance. For each value of the random dependent variable the error can take negative, zero or positive values. Some values of the independent variables in the present case cause the dependent variable to take its limiting value, zero. OLS assumptions lead us to expect to observe positive and negative deviations from zero but we do not. The error distribution for zero values of the dependent variable is truncated and is not the error distribution on which OLS is based.

The queue length relationship to be estimated is described by the tobit model

$$(25) \quad \begin{aligned} y_j &= x_j'\beta + e_j && \text{if } x_j'\beta + e_j \geq 0, \\ &= 0 && \text{otherwise} \quad j=1,\ldots,T \end{aligned}$$

Alternatively, we can restate the tobit

$$(26) \quad \begin{aligned} y_j &= x_j'\beta + e_j && \text{if } e_j \geq -x'_j\beta, \\ &= 0 && e_j < -x'_j\beta \quad j=1,\ldots,T \end{aligned}$$

where the e_j are independent and $N(0,\sigma^2)$. β and σ^2 are estimated using the T observations and maximum likelihood procedures (Amemiya). The likelihood function includes both the density and normal cumulative density functions. The normal equations are highly nonlinear and must be solved numerically. Amemiya (1973) shows that maximum likelihood estimates of β and σ^2 are consistent and have asymptotically normal distributions. Rigorous developments of the tobit estimators can be found in Amemiya, Maddala (1983), and Fomby.

An undocumented but oft-repeated rule of thumb is that a quantitative difference in parameter estimates between OLS and tobit techniques will result if more than 15 percent of the sample is at the bound or deleted from the random sample (Murrell, et al). A significant concentration of zero values will be reflected in the cumulative distribution and density function and estimates of β by the tobit model will differ from the OLS estimates of β.

An informal test of the seriousness of the limited dependent variable problem was conducted by estimating the same models by OLS and tobit procedures and comparing the results. The estimates of β showed an obvious difference between the two methods for the queue size and downtime functions. In the data samples nearly 50 percent of the queue values equaled zero. As a result the queue length function was estimated using the tobit model.

SPECIFICATION OF THE MODEL

The model described above could not be estimated by the prior formulation of the model based on a priori reasoning. Economic theory, engineering science, queuing theory and field experience provided little prior information about the lockage process. Instead the model was formulated using an experimental approach guided by professional judgment.

Hundreds of formulations of the model were tried with the smaller experimental data set. Theory provided a sound basis for the inclusion of a core group of critical variables. Many of the interaction terms had no intuitive meaning because they were spurious in nature. Other interaction terms were not statistically different from zero. As a result most interaction terms were restricted to zero. During the formulation process restricted relationships of the form:

$$(27) \quad \begin{aligned} &H_0: \beta_{ij} = \beta_{kl} = \ldots = \beta_{mn} = 0 \\ &H_1: H_0' \end{aligned}$$

were tested using OLS results of single equation models and the F statistic:

$$(28) \quad F = (R^2/(K-1))/((1-R^2)/(N-K))$$

where N is the number of observations and K the number of variables. Invariably the F statistic was too low to reject H_0. All of this testing was conducted prior to estimation of any equations with the tobit model.

A positive and decreasing marginal product was assumed in the model formulation. Interaction terms containing lock capital were not statistically significant. Lock capital was entered into the model in a variety of forms. The square root transformation of lock capital was finally chosen. Sensitivity of the model results to the form of the lock capital transformation is presented in the next chapter.

ESTIMATION RESULTS

Table 4-1 contains a summary of the variables appearing in the estimated system of equations. All cumulative variables are annual values. Variables with an asterisk are lock-specific, those without are lockage-specific. Estimation results and the explicit form of the model are presented in Table 4-2.

Lock capital is negatively related to service time as shown in equation (15). Total annual tonnage at the lock increases service time. As the annual number of lockages at the lock increase service time declines. This may be reasonable to the extent that with tonnage accounted for lockages are a good indicator of experience of the personnel.

The number of chambers has the expected sign. A larger number of chambers implies that more than one chamber is in use at a time. Resulting traffic congestion could increase service time. Even if the chambers are not used simultaneously the presence of multiple chambers is a strong indication of heavy usage and a positive relationship to service time.

Tonnage per tow and length of tow for a specific lockage increase the service time as expected. An increase in the number of barges decreases the service time. If the length of a tow and its tonnage are fixed a wider flotilla, i.e., one with more barges, can apparently be moved through the chamber more quickly than a flotilla with fewer barges and deeper draft. Such an explanation is consistent with the work of [illegible] (1969).

TABLE 4-1
DESCRIPTION OF VARIABLES

VARIABLE	UNITS OF MEASURE	MINIMUM	MAXIMUM	MEAN
Y_1=service time	minutes per tow	4	453	44.5
Y_2=queue length	# of tows	0	32	1.6
Y_3=transit time	minutes per tow	4	6315	113.4
K=lock capital*	$(\$1,000,000)^{.5}$	13.4	272.8	88.5
X_1=annual tonnage*	million lbs.	0.07	70.6	19.6
X_2=number of chambers*	count	1	2	1.4
X_3=entry difficulty	index	0	8.0	1.0
X_4=direction of lockage	1=upstream 2=downstream	1	2	1.5
X_5=lift performance*	index	.01	1.0	.43
X_6=lock lnth,X_{10} interaction	1,000 feet	0	1200	483.4
X_7=lock wdth,X_{20} interaction	1,000 feet	0	363.3	174.5
X_8=barges	# per tow	0	30	4.5
X_9=tonnage per tow	1000 pounds	0	68700	3799
X_{10}=tow length	feet	0	9085	476
X_{11}=lockages per year*	1000 lockages	523	15334	5704
X_{12}=X_3,X_4 interaction	index	0	3.5	1.1
X_{13}=exit dif,X_4 interaction	index	0	3.8	1.1
X_{14}=stall this lockage	1=yes 0=no	0	1	0.0
X_{15}=arrival rate	tows/minute	0.000	2	.08
X_{16}=no.of commercial tows*	1000 annually	.075	12.4	4.2
X_{17}=lock-rel'd downtime*	1000 minutes annually	0	90312	7354
X_{18}=no. of stalls*	annual count	0	1069	114
X_{19}=tow-lock length ratio	index	0	3.7	0.7
X_{20}=fly entry	1=yes 0=no	0	1	0.5
X_{21}=fly exit	1=yes 0=no	0	1	0.5
X_{22}=exchange entry	1=yes 0=no	0	1	0.3
X_{23}=exchange exit	1=yes 0=no	0	1	0.3

TABLE 4-2
FINAL ESTIMATION RESULTS
(t-statistic)

<u>SERVICE TIME FUNCTION</u>

Y_1=5.736-1.706K+5.364X_1+5.338X_2+10.787X_3-6.173X_4+13.165X_5
(6.3) (-18.8)(29.4) (11.8) (16.9) (-11.4) (20.3)
-.047X_6+.889X_7-.547X_8+.345X_9+.034X_{10}-.851X_{11}-5.529X_{12}
(-27.8)(16.4) (-8.1) (9.4) (25.4) (-14.9)(-4.5)
+24.343X_{13}+18.089X_{14}
(46.1) (15.2)

Standard error of the regression=326.4122 R^2=.649 n=15104

<u>QUEUE LENGTH FUNCTION</u>

Y_2=-4.545+.013Y_1-.014X_1-.249X_2+2.594X_{15}+.745X_{16}-.024X_{17}+.007X_{18}
(-29.6)(10.8) (-3.3) (-8.4) (19.9) (50.6) (-8.4) (31.2)

Standard error of the regression=3.9956 n=15104

<u>TRANSIT TIME FUNCTION</u>

Y_3=20.674+1.099Y_1+45.502Y_2+136.822X_{14}+39.482X_{19}-24.643X_{20}
(3.6) (16.4) (99.3) (11.7) (12.7) (-5.6)
-35.026X_{21}-33.963X_{22}-55.371X_{23}
(-8.1) (-7.6) (-12.3)

Standard error of the regression=31242.38 R^2=.517 n=15104

If a stall occurs during a particular lockage the service time increases as expected. The direction of the lockage is also significant. The observed negative sign is as expected. The ratio of the average lift per lockage to the design lift is also positively related. Values of the lift index less than one mean a relatively low lift hence less time is needed to fill and empty the chamber.

Entrance and exit conditions were consistently mentioned as important factors in determining service time by Corps experts. None of the lock characteristic variables captured these effects in a meaningful way. Indices of approach conditions were created from the available data. For vessels entering the lock the actual entry time was scaled by the average entry time for that year. A value greater than one implies an entry more difficult than average. Values less than one imply entries less difficult than average. A similar index was created for exit conditions though it does not appear in the model. These variables are lock specific indices of lockage specific conditions. Only the entrance condition index was empirically detectable and the sign was positive indicating more difficult approach conditions take more time.

The interactions of entrance and exit conditions just defined with the direction of the lockage are both intuitively appealing and empirically important. The interaction of entrance conditions and direction is characterized by a negative relationship. Large values of this term imply entrances with the current and more difficult than average entrance conditions. Small values imply entrance conditions less difficult than average. The negative sign implies that when entering a lock having the current with you is more important than the relative entrance conditions. A favorable current decreases service time.

The interaction of exit conditions and direction is positively related to service time. When exiting a lock difficult exit conditions are apparently more significant than whether the current is with or against the tow. A moment's reflection suggests these results are reasonable. When entering a lock a tow must enter the current and come to a stop in the lock chamber. Current direction is important. When exiting a lock a tow starts from a dead stop and normally will not be influenced by current direction until after leaving the chamber.

Two other interaction terms combine the interaction of the individual tow's length and the dimensions of the lock. The interaction of tow length and lock length is negatively related to service time. Long tows at long locks are a good match. Long tows at short locks often require multiple cuts to transit the lock and this takes more time. The sign is reasonable.

The interaction of tow length and lock width is positively related to service time. This is also reasonable. Long tows at wide locks may have to be reconfigured before transiting the lock if the lock is wide rather than long. Even if the lengths are closely matched the relative width can cause maneuvering problems within the chamber that take more time.

Estimation of the relationship explaining queue length confirms the hypothesized relationships presented earlier in this chapter. Service time is positively related to queue length. The number of stalls increases the mean queue as we would expect. If annual lock-related downtime, i.e. stalls due to lock malfunction,testing or maintenance, decreases the mean queue length is expected to be shorter. Lock-related stalls are often scheduled and publicized well in advance of their occurrence to allow shippers to avoid unusually long queues and delays. When unscheduled lock malfunction stalls are of long duration shippers again have enough time to avoid the lock once the problem has been assessed and publicized. For very short duration stalls the effect on queue size is negligible. Only stalls with no advance warning or of insufficient duration to alter shipper's modal choices will lead to a positive relationship between queue size and annual downtime. This is generally considered to be the relatively smaller effect and overall we expect the observed sign.

Exogenous demand for lockages measured as the number of commercial lockages per year is positively related to queue length. Total annual tonnage is negatively related to queue size. With demand accounted for total tonnage is an indicator of lock and tow personnel experience and the sign is reasonable.

The more chambers there are at a lock the more tows can be processed and the shorter the queue will be. The negative relationship is as expected until we note above that the number of chambers increases service time. Noting that service time is accounted for in the model we can revert comfortably to the argument that, service time constant, queues are smaller the more chambers available.

Queuing theory and common sense tell us the time between vessel arrivals is an important determinant of queue length. This time element best enters the model inversely as the number of vessels arriving per minute or the arrival rate. A positive sign is observed as expected.

Service time and queue length are positively related to transit time as hypothesized in equations (16) and (18). The service time coefficient is not significantly different from one. The presence of a stall during a particular lockage greatly increases the length of that lockage. The ratio of the tow's length to the lock's length is also positively related to transit time. This is consistent with common sense and observed performance.

An additional set of factors found to be significant in determining transit time are dummy variables describing the type of entry and exit that occurred. A fly exit or entry means the lock was open and waiting for the arriving or departing tow. An exchange entry or exit means as one tow exits/enters another waiting tow enters/exits without delay. All of these variables are negatively related to transit time as expected.

Using this estimated system of equations, mean values of exogenous variables and forecasting models described below it is possible to express transit time as a function of lock capital, K. A point estimate of this function for Lock and Dam 13 on the Mississippi River (L&D 13) is:

(29) $\text{Transit time} = 105.919 - 1.426(K)^{.5}$

EVALUATION OF ESTIMATES

To evaluate the theoretical and statistical meaning of the results three sets of criteria were used. First, are the a priori criteria which are determined by prior knowledge of the functioning of the system. Second, are the statistical criteria determined by statistical theory. Third, are the econometric criteria determined by econometric theory.

The a priori criteria refer to the sign and size of the parameters. For the most part all parameters are of the expected sign. Significantly, the sign of the control variable, lock capital, is negative (indicating a positive marginal product) and increasing (indicating a decreasing marginal product) in all three formulated relationships as predicted by theory. The magnitude of the parameters seems reasonable.

The marginal product of lock capital at L&D 13 based on equation (29) above is :

(30) ∂transit time/∂lock capital$=-.713(K)^{-.5}$

The function is negative as expected and the derivative of (30) is positive. The marginal values of lock capital in terms of service time, and queue length and their parent functions are as follows:

(31a) ∂Service time/∂Lock capital$=-.5853(K)^{-.5}$

(31b) Service time$=58.8042-1.1706(K)^{.5}$

(32a) ∂Queue length/∂Lock capital$=-.0078(K)^{-.5}$

(32b) Queue length$=1.0897-.0156(K)^{.5}$

Equations (31) are functions. Equations (32) are only point estimates of functions because they are based on the tobit model and depend on specific values of the cumulative distribution and density function.

The parameter estimates have small standard errors in each case. As the t-statistics show the parameter estimates are relatively reliable. The square of the correlation coefficient is statistically significant and relatively large for a cross sectional analysis for each of the individual OLS equations.

The second-order tests or tests of the statistical tests are based on econometric theory. If the assumptions of the econometric methods applied are not satisfied then either the estimates do not possess their desirable properties or the standard errors of the estimates become unreliable.

Care has been taken in developing the model presented above. The potential for misspecification of the model has been minimized. There is no evidence to suggest that the system is anything but recursive, eliminating concerns about identification of the system. With a cross sectional analysis there is no concern about auto-correlated error terms. There is nothing about the processes involved that suggests heteroscedasticity. The choice of independent variables was made after extensive experimentation and testing using all available theory and a priori information. Error terms are assumed to be normally distributed.

In summary, every reasonable effort has been made to insure that no econometric criteria have been violated.

ROBUSTNESS OF MODEL

Single equation estimation of the model's relationships limits the potential for using different estimation techniques. The parameter estimates for the tobit model are compared in Table 4-3 to the biased OLS estimates and the OLS estimates corrected by Greene's (1981) method of dividing the biased OLS estimates by the sample proportion of non-limit observations.

Sensitivity of the model formulation to the functional form of lock capital is presented in Table 4-4. Lock capital coefficients and marginal products cannot be compared directly because of differences in the capital variable transformation. Marginal products are based on the 1984 estimate of capital at L&D 13, $65 million. There is little difference in the value of the marginal products which should be interpreted as a decrease in minutes per tow.

One of the first issues addressed in the model formulation, i. e., choice of the lock capital variable is also critical to the solution of the dynamic model. The lock capital variable identified in Chapter 3 represents one of an infinity of lock capital mortality distributions. It is interesting to see how the use of other capital variables affects the parameter estimates and marginal products. The alternate variables used are described in Chapter 3 and Appendix 2. The results of this sensitivity analysis are presented in Table 4-5 for the critical lock

TABLE 4-3

COMPARISON OF TOBIT OLS AND ADJUSTED OLS ESTIMATES

INDEPENDENT VARIABLE	DEPENDENT VARIABLE QUEUE LENGTH TOBIT	OLS	GREENE
Constant	-4.545	-.411	[illegible]
Service time	.013	.006	.013
Annual tonnage	-.014	-.002	-.005
No. of chambers	-.249	-.391	-.833
Arrival rate	2.594	1.078	2.295
Annual com'l tows	.745	.472	1.006
Downtime	-.024	-.015	-.032
No. of stalls	.007	.006	.013

TABLE 4-4

COMPARISON OF PARAMETER AND MARGINAL PRODUCT ESTIMATES VARYING THE FORM OF CAPITAL

LOCK CAPITAL VARIABLE	SERVICE TIME	MARGINAL PRODUCT
$K^{.1}$	-.28.2730	$-3.444K^{-.9}$ = -.080 minutes
$K^{.3}$	-4.4129	$-1.612K^{-.7}$ = -.087 minutes
$K^{.5}$	-1.1706	$-0.998K^{-.5}$ = -.088 minutes
$K^{.7}$	-0.3512	$-0.300K^{-.3}$ = -.086 minutes
$K^{.9}$	-0.1097	$-0.200K^{-.1}$ = -.132 minutes

TABLE 4-5

COMPARISON OF PARAMETER AND MARGINAL PRODUCT ESTIMATES
VARYING LOCK CAPITAL VARIABLES

LOCK CAPITAL VARIABLE	DEPENDENT VARIABLE SERVICE TIME	MARGINAL PRODUCT
K	-1.1706	$-0.713K^{-.5}=-0.088$ minutes
KSL150	-1.2692	$-0.849K^{-.5}=-0.105$ minutes
KGI150	-1.2725	$-0.775K^{-.5}=-0.096$ minutes
K67150	-1.2075	$-0.807K^{-.5}=-0.100$ minutes
K50150	-1.2487	$-0.835K^{-.5}=-0.104$ minutes
K84	-1.1802	$-0.789K^{-.5}=-0.098$ minutes
K98100	-1.1630	$-0.708K^{-.5}=-0.088$ minutes
KSL100	-1.2901	$-0.863K^{-.5}=-0.107$ minutes
KGI100	-1.2913	$-0.863K^{-.5}=-0.107$ minutes
K67100	-1.1990	$-0.802K^{-.5}=-0.099$ minutes
K50100	-1.2695	$-0.849K^{-.5}=-0.105$ minutes

capital coefficients. All coefficients are statistically significant at the 0.999 level. Again 1984 capital at L&D 13 has been used to estimate marginal productivities.

The limited range in estimates of the marginal product of capital of about one-tenth of a minute per tow due to the use of different series of lock capital is particularly interesting. There is no a priori information that suggests which estimates are the most reasonable. K has been chosen as the best estimate of lock capital as described in Chapter 3. Definitions of the remaining variables don't lend themselves to short descriptive names. Definitions of these variables are contained in Appendix 2.

Regardless of the choice of lock capital variable the range in marginal productivities of lock capital is about one-tenth of a minute per tow. This is the first indication that despite the wide ranging and serious questions about the choice of the lock capital variable the choice of the variable does not lead to widely varying results.

FORECASTING WITH THE ESTIMATED MODEL

The parameters of the estimated equations and the depreciation function for lock capital can be used to generate a time series of values for transit time. In solving the dynamic model one value of interest is the change in transit time that results from rehabilitation. Forecasting values for transit time in the framework of the recursive model developed above requires forecasts of each of the endogenous variables. The forecasts are made from the bottom of the recursive system up.

Forecasting with the OLS model is straightforward. Values of the exogenous variables are assumed for the forecast period. Mean values of exogenous variables for the lock for which the forecast is being made are used. In the absence of better information the disturbance term is assumed to take the value zero. The forecasting model is simply:

$$(33) \quad Y_i = \beta' X_i$$

All values are point estimates and the i subscript indicates a forecast value. Forecasts of service time and transit time use the OLS model.

Forecasting with the tobit model is more involved. The tobit estimate of the β vector is for the latent dependent variable. The latent queue is the theoretically achievable queue length which includes queues of negative length. Predictions about the observed non-negative queue lengths are wanted. There are two such predictions that can be made. One is conditional on $Y_i > 0$ and ignores information for zero queue lengths, the other is unconditional and uses information from all queue sizes greater than or equal to zero.

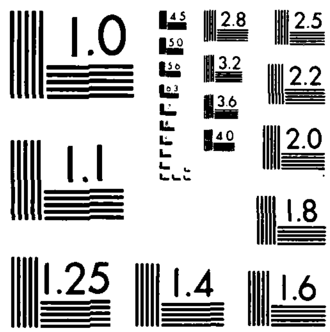
The first prediction is given by:

$$(34) \quad E(Y_i \mid Y_i > 0) = \beta' X_i + E(u_i / u_i > -\beta' X_i) = \beta' X_i + \sigma(\phi_i / \Phi_i)$$

where σ is the standard error of the regression and ϕ_i and Φ_i are the density and distribution functions respectively defined as:

AD-A184 386 LOCK REHABILITATION A PUBLIC INFRASTRUCTURE PROBLEM: THE VALUE OF INCREAS (U) MARYLAND UNIV COLLEGE PARK DEPT OF AGRICULTURAL AND RESOURCE E C E VOE JAN 87 2/2

UNCLASSIFIED IWR-87-R-1 DACW72-85-C-0012 F/G 13/2 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

$$(35)\quad \phi_i = \sigma f_i = (1/(2\pi)^{.5})\exp((-\beta' X_i)^2/2\sigma^2)$$

$$(36)\quad \Phi_i = F_i = \int_{-\infty}^{\beta' X_i/\sigma} (1/(2\pi)^{.5})\exp(-t^2/2)\,dt$$

The prediction using all observations is obtained by:

$$(37a)\quad E(Y_i) = P(Y_i>0)E(Y_i/Y_i>0) + P(Y_i=0)E(Y_i/Y_i=0)$$

$$(37b)\quad = \Phi_i(\beta' X_i + \sigma(\phi_i/\Phi_i) + (1-\Phi_i)0$$

$$(37c)\quad = \Phi_i \beta' X_i + \sigma\phi_i$$

which is the sum of the probability weighted expected values. Forecasting model (37c) is chosen for forecasting queue length because it uses all of the information available.

The estimation results of this chapter are used in the following chapter to solve the model for rehabilitation of Lock and Dam 13 on the Mississippi River.

CHAPTER 5

SOLVING THE MODEL

INTRODUCTION

In this chapter the model and estimation results are used to estimate maximum benefits of improved mean lock performance at Lock and Dam 13 on the Mississippi River. The sensitivity of these benefit estimates to changes in the remaining life of lock capital, interest rates, the functional form of lock capital, useful life of locks and dams, lock capital variables and the depreciation pattern of the rehabilitated lock, the age of the asset, and the initial level of lock capital is examined.

LOCK AND DAM 13 ON THE MISSISSIPPI RIVER

The major objective of this research is to estimate the benefits which accrue due to improved mean performance of the lock. The main criterion in selecting a test case for estimating these benefits was to select a site for which data is available.

The most logical sites from which to choose were those already being considered for major rehabilitation by the Corps. Lock and Dam 13 on the Mississippi River the subject of a December, 1984 rehabilitation study was chosen as the test case.

L&D 13 is located at river mile 522.5 on the Mississippi River between Whiteside County, Illinois and Clinton County, Iowa. It is one of 29 locks and dams on the Mississippi River which operate as a system to provide 9 feet of navigational depth from St. Louis, Missouri to Minneapolis, Minnesota. L&D 13 provides a navigational depth of 9 feet from river mile 522.5 to river mile 556.7. The main lock is 660 feet long and 110 feet wide. The emergency lock , which is only partially constructed, is 360 feet long and 110 feet wide. The maximum lift is 11 feet. The dam is 14,456 feet long. L&D 13 has never had a major rehabilitation.

The Rock Island District of the Corps of Engineers proposes resurfacing the overflow section of the dam, repair and maintenance work on the dam's tainter and roller gates, repair and maintenance on the lock walls and mitre gates, and additional scour protection to slow further deterioration and to extend the useful life of the structure. The estimated first cost of the recommended rehabilitation plan in 1984 dollars is $12.4 million. The present value of catastrophe benefits for this project is $37.7 million based on a 50-year planning horizon and an interest rate of 8.375 percent.

MODEL SOLUTION ASSUMPTIONS

Before the model presented in equation (1) of Chapter 2 can be solved several issues must be resolved. The period of analysis from t_0 to T is assumed to be 50 years. The discount factor for planning horizons beyond 50 years becomes so small that it renders values from these years negligible. A 50-year period is also consistent with the Corps' decision making period of analysis. The model's relative sensitivity to a 50-year horizon is tested. The base year, t_0, is defined as the earliest year in which the project could be completed, is assumed to be 1990.

The applicable rate of interest for evaluating public works projects and future streams of benefits is one of the most controversial in the literature. The rate sought is the rate at which society discounts a marginal addition to consumption in the future relative to the present. There are two fundamentally different views on what that rate should be. One is that the rate should equal the market rate of interest or the opportunity cost of capital. Proponents of this view argue this rate incorporates risk premiums and forces capital projects to meet the market's test of efficiency.

The opposing view argues that the market rate is too high. Risk-pooling and risk-spreading opportunities with public works projects are said to reduce the social costs of risk bearing to zero or near-zero levels. Proponents of this view also argue that at the market rate of interest the marginal social benefit from a household's saving for future generations exceeds the marginal private benefits to the household. Each household therefore undersaves and the rate at which future consumption should be discounted is below the market rate because of this externality. The market rate of interest equals the social discount rate only if this intergenerational externality is negligible. I purposely sidestep this controversy and use the interest rate mandated by Congress for the Corps of Engineers in Public Law 93-251. The current

8.625 percent rate is used. The sensitivity of the model's solution to higher and lower rates is tested.

Forecasts of commodity flows on the Upper Mississippi River from the Comprehensive Master Plan for the Management of the Upper Mississippi River System, Technical Report A Navigation and Transportation were used to determine the exogenous demand for lockages at L&D 13 throughout the period of analysis. Total commodity flows of 24.87 million tons in 1990 were projected to fall to 21.3 million tons by 2040 under the most favored scenario of future demand conditions in the report. Most of the decline was projected to occur between 2010 and 2040. Other scenarios project slight increases in demand.

To simplify the analysis for exposition purposes and recognizing the uncertainty inherent in the various projections of demand for lockages at L&D 13 a constant commodity flow was assumed. The number of tows passing through the lock is assumed to remain constant at the 1984 level of about 1,100 commercial tows. This is the assumed value of L in the model.

Estimates of hourly costs of towboat and barge linehaul operation on the Mississippi River system were obtained from the "Army Corps of Engineers' Fiscal Year 1986 Reference Handbook". The costs are based on information obtained directly from tow and barge companies and other sources. Hourly linehaul costs range from a low of $137/hr. for a 1200 HP tow to $663/hr. for a 10,000 HP tow. Barge costs are estimated to be about $3/hr. per barge.

Data from L&D 13 for October 1984 were used to determine that the average tow size was in the 5,000 to 7,000 HP range, near the lower end of the scale. The hourly cost of a tow this size is about $424. With an average of about 11 barges per tow barge costs are an additional $33/hr. for a total estimated hourly cost of $457. This is the value for V in the model. Each minute saved by an increase in lock capital productivity lowers the effective price of lockages at L&D 13 by almost $8 per lockage.

Rehabilitation costs are incurred over several years. Typically, first year expenditures for final design and preliminary site work are relatively small. A variable period is then required to construct the rehabilitation project. In this evaluation the multi-year period is identified by the year in which the project is completed. For example, a 4-year construction period begun in 1987 will be complete in 1990. The optimal time, t_1, to undertake the rehabilitation will be expressed in terms of the year in which the project is completed. Thus, the optimal timing question is modified to the choice of the year in which it is optimal to have the project operational.

Chapter 3 details arguments for assuming that lock capital at a lock depreciates according to the function

(1) $\delta = 150\text{-}age/150\text{-}.9866*age$

and has a 150-year useful life. The question remaining is, what happens to the remaining life and depreciation pattern of capital stock if a lock is rehabilitated?

L&D 13 was 46 years old in 1984. If it is rehabilitated in 1990 at age 52 does it have a remaining life of 98 years or something different?

Does the original lock capital have the same remaining life as the rehabilitation capital?

If a lock has a remaining life of 30 years it is unreasonable to rehabilitate it in such a way that the rehabilitated elements last 120 years longer than the rest of the structure. Likewise if a lock has a 130-year remaining life it is not rational to fix parts of it to last 30 years knowing full well they must be repaired again at that point. The huge fixed costs of rehabilitation and the relatively stable technology preclude the rationality of such shortsighted strategies. I assume that rehabilitation capital has a useful life identical to that of the capital stock in existence at the time of the rehabilitation and this useful life is 150 years. The former is assumed simply because it seems irrational to make any other assumption. The latter because rehabilitation will not shorten the useful life of a structure and most Corps' engineering experts agree that rehabilitation can make a lock as good as new. In the absence of any evidence to the contrary a 150-year remaining useful life is assumed for a rehabilitated lock. The sensitivity of model results to this assumption is tested.

Care has been taken to develop the most reasonable set of assumptions possible given the available data and state of knowledge about the phenomena involved. The sensitivity of the benefit estimates to these assumptions will be presented in a later section.

METHOD OF SOLUTION

The model has an explicit transformation equation based on (1) above. It has constant values for the number of tows, L, and tow-hour costs, V. Transit time has been estimated as a function of lock capital. Nonetheless the model does not have an easily obtained analytical solution. Transit time expressed as a function of lock capital is complicated by the tobit forecasting model. Because the dynamic model can be reduced to a static model when the level of rehabilitation effort is known there is a simpler method of solving the model that does not require explicit solution of the first order conditions.

Rehabilitation of a lock is an engineering option only once specific problems have been identified. There are typically a finite and small number of engineering solutions that can solve the problems. Because only a few rehabilitation alternatives exist the dynamic model can be reduced to a series of simple static models like the one shown in equation (15) of Chapter 2.

The model is solved separately for each rehabilitation alternative choosing only the optimal time, t_1, to rehabilitate the lock. After the model is solved for each rehabilitation alternative it is a simple matter of choosing the rehabilitation alternative which maximizes net benefits.

The method used to solve the model was the golden search which is simply a structured trial and error method. The solution was structured to estimate the benefits assuming t_1 to be the years 1990, 2000, 2010, 2020, 2030 and 2040. The result of this initial analysis identifies the time period or cell containing maximum net benefits. A year-by-year analysis of this cell determines the optimal time to rehabilitate the lock.

Using the estimation results of the previous chapter and the above assumptions an estimate of the lock capital stock was made from the year initial construction of the structure was completed through the 50-year planning horizon. These are the lock capital values for the no rehabilitation alternative, i. e., R=$0. The transition equation for this alternative reduces to:

(2) $K_t - K_{t-1} = \delta K_{t-1} \qquad t=1, \ldots, T$

where δ is the depreciation function in equation (1). When these lock capital values are substituted into the system of equations estimated in Chapter 4 estimates of the endogenous variables are obtained for the no rehabilitation alternative. Figure 5-1 presents time series for lock capital and the functionally dependent service time, queue length, and transit time per tow for L&D 13 assuming no rehabilitation.

Next, the transition equation,

(3) $K_t - K_{t-1} = R - \delta^* K_{t-1} \qquad t=t_0, \ldots, T$

was used to generate a second time series of lock capital values for the period t_0 to T. For example, using a depreciation function like (1) and R=$12.4 million equation (2) is used to estimate the stock of lock capital in t_0-1 and (3) is used to estimate a lock capital series for

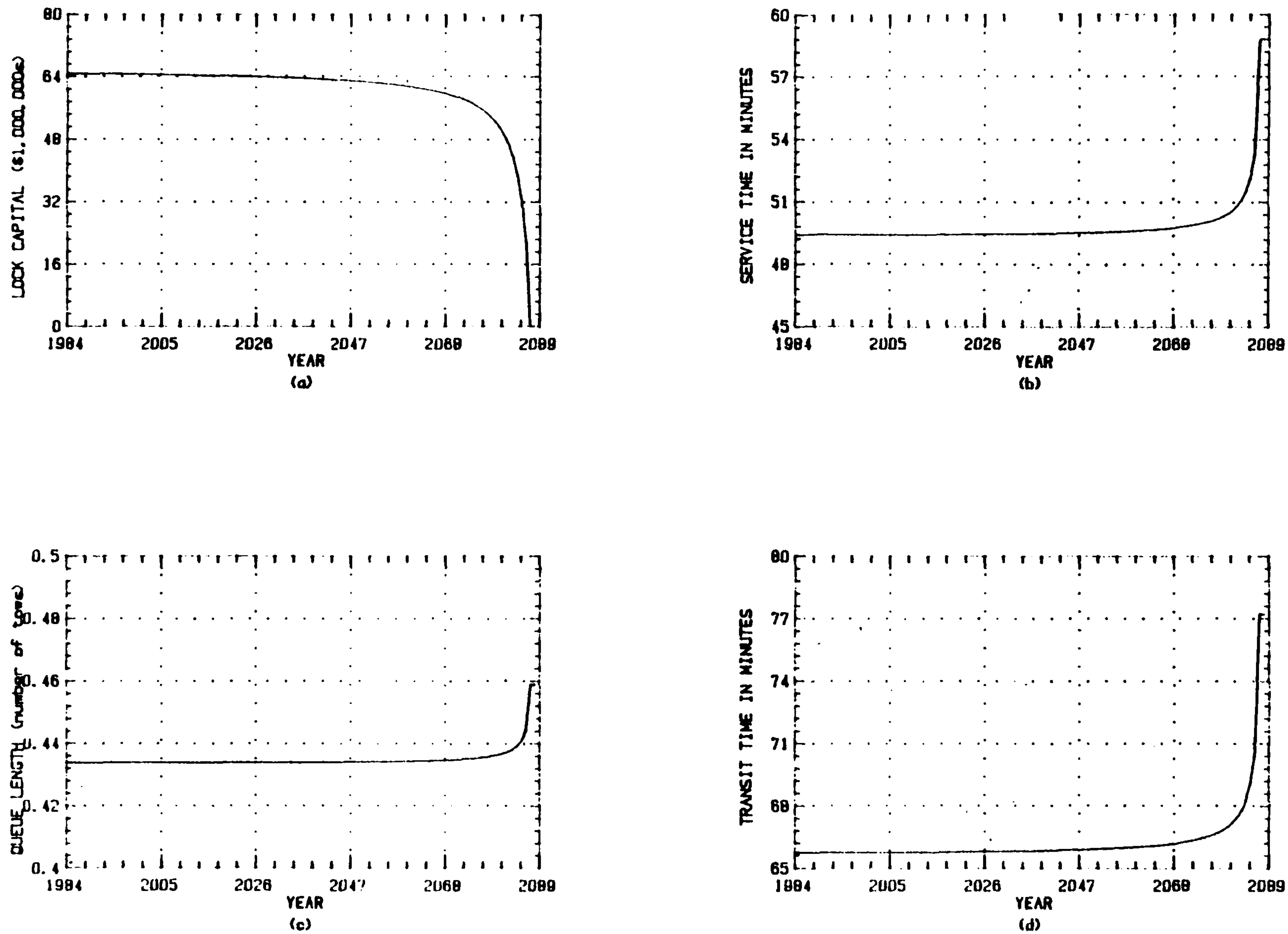


FIGURE 5-1: L&D 13 W/ NO REHABILITATION

the rehabilitated lock. The age factor in (1) is adjusted to reflect the year of implementation of the rehabilitation and accounts for the difference between δ of (2) and δ^* of (3). In other words if age=52 at the time of rehabilitation then in t_1 age will equal 0. The new lock capital variable reflecting a specific level of rehabilitation is used to forecast values for all the endogenous variables in the system.

With estimates of transit time per tow for each year of the planning horizon it is a simple matter of subtraction to compute the time savings for the average lockage each year. This time savings per tow is multiplied by the number of tows to get total time savings. The total time saved is multiplied by the value of the time and the annual value is discounted to the base year 1990. The present value of these benefits are compared to the present value of the rehabilitation costs. The estimation procedure can be summarized by:

$$(4) \quad PVNB=\sum_t((TL_t(K_{Nt})-TL_t(K_{Rt}))LV)-R_t)(1+r)^{-t}$$

where PVNB is the present value of net benefits, r the discount rate, K_N lock capital if there is no rehabilitation and K_R lock capital with rehabilitation. Capital values are square root transformations.

RESULTS OF MODEL SOLUTION

This section begins by evaluating maximum benefits from the optimal timing of the rehabilitation project recommended by the Corps of

Engineers for L&D 13. This evaluation will serve as a standard measure against which the sensitivity analysis results can be compared.

The benefits estimated by the Corps for the $12.4 million rehabilitation plan are the "catastrophe" benefits described briefly in Chapter 2. The present value of avoided catastrophe costs is $37.69 million .

Table 5-1 presents estimated benefits from the $12.4 million rehabilitation of L&D 13. Benefits are presented for several values of t_1. Net benefits are never positive but net benefits are optimized in the last year, T, of the planning horizon. The estimated benefits are of a relatively small magnitude with a present value that never exceeds $.07 million. Compared to "catastrophe" benefits of $37.69 million these benefits are trivial in magnitude.

The first hint that these benefits may be small was obtained from the marginal product estimates presented in the last chapter. Figure 5-2 shows that the improvement in mean transit time is less than two minutes per tow for most of the planning horizon which ends in 2040. The time paths shown are based on no rehabilitation and rehabilitation completed in 1990. Clearly a $12.4 million rehabilitation project at L&D 13 cannot be justified on the basis of net welfare gains if improvement of mean lock performance for commercial tows is the only benefit. Rehabilitation should not be undertaken, or if it must it should be put off as long as possible.

Figure 5-3 presents a three dimensional illustration of how the present value of benefits vary with transit time savings per tow over time. The effect of the discount factor is obvious.

TABLE 5-1
BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
DUE TO LOCK REHABILITATION
($1000s)

ITEM	YEAR OF REHABILITATION 1990	2000	2010	2020	2030	2040
Total time saved hours	1011	814	616	416	217	19
Total value of time saved	$462	$372	$281	$190	$99	$8
Present value of time saved	67	29	12	5	2	0
Present value of rehab costs	14540	7230	3160	1380	600	260
Net benefits	-14473	-7201	-3148	-1375	-598	-260

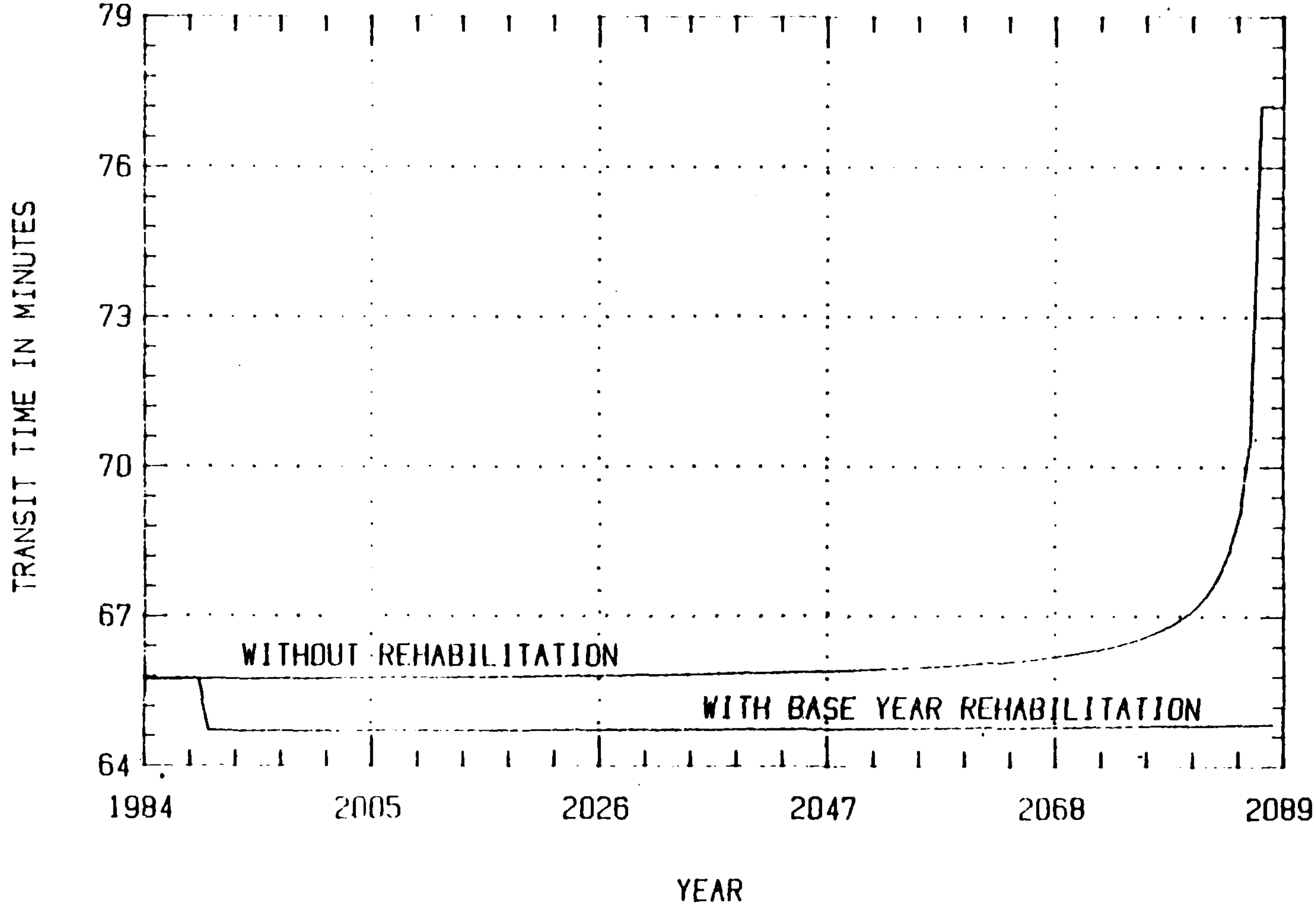


FIGURE 5-2: PLOT OF TRANSIT TIMES

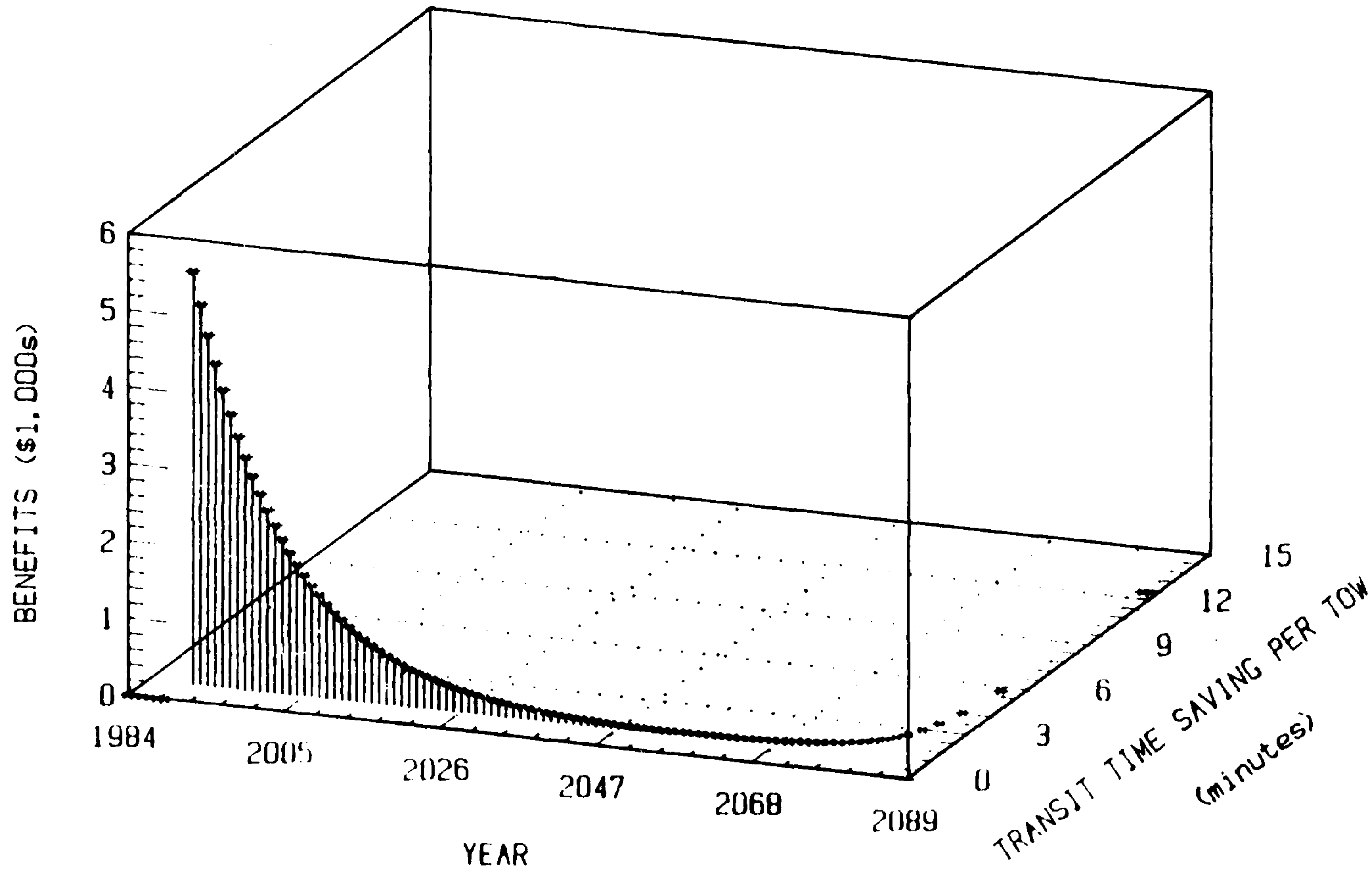


FIGURE 5-3: PLOT OF BENEFITS VS YEAR & TRANSIT TIME SAVINGS FOR L&D 13

Costs in Table 5-1 include the $12.4 million first costs of construction plus interest during construction of $2.14 million estimated by the simple formula

(5) IDC=years of construction*r*first costs of construction/2

Costs always exceed benefits in this case. The magnitude of the difference between costs and benefits becomes less over time simply because of the geometrically decaying weight that is given to the value of this difference in the more distance future. Though the time savings are also less in the future the value of these savings was minimal to start with. The discount function continues to shrink the magnitude of the costs as the timing of the rehabilitation is moved farther into the future. The result is that the farther into the future we look the smaller is the net welfare loss. Over the 50-year planning horizon the present value of benefits fall by $67,000 while the present value of costs fall by $14,280,000.

Thus far I have argued that the optimal time to implement the $12.4 million alternative is in the last year of the planning horizon if it must be done and not at all if a net welfare gain is desired. There are other rehabilitation alternative. Each is identified in the "Rock Island District's Reconnaissance Report" and is not described here beyond the dollar value of the rehabilitation effort. Additional alternatives have been constructed from among the different options for addressing the lock and dam problems contained in the report. This has been done so as to increase the number of alternatives to better illustrate the range of results.

Table 5-2 presents the present value of benefits for rehabilitation efforts ranging from $6.6 million to $19.4 million.

Benefits remain small relative to costs and do not rise in proportion to rehabilitation effort. The diminishing marginal product of rehabilitation capital results in increases in output, hence benefits, which are smaller than the corresponding increases in input, rehabilitation effort.

It is clear from previous results and the information in Table 5-2 that smaller projects have larger net benefits (actually, smaller net losses) than do large projects. To see this simply note that going from a $6.6 million rehab to a $7.7 million rehab incurs additional costs of $1.1 million while an additional $6,000 in benefits accrue. This trend holds across rehabilitation efforts and optimal t_1 choices. The optimal level of rehabilitation for L&D 13 considering this one type of benefit only is $0 resulting in net benefits of $0 which exceeds the net loss of all other rehabilitation alternatives. The optimal timing for every non zero rehabilitation effort is the terminal year.

What happens to benefit magnitudes and the optimal timing of the project if we look at a longer planning horizon? With a 100 year planning horizon total time saved by the $12.4 million plan implemented in the base year jumps from 1,011 hours with a 50-year planning horizon to 2,867 hours with a 100 year horizon. The current value of these time savings are $462,000 and $1,310,000. The present value of these savings are $67,000 and $68,000, however. The discount function

TABLE 5-2
PRESENT VALUE OF IMPROVED MEAN L&D 13 PERFORMANCE BENEFITS
FOR ALTERNATIVE PLANS

YEAR OF	LEVEL OF REHABILITATION EFFORT ($millions)						
COMPLETION	$6.6	$7.7	$8.9	$9.2	$12.4	$13.4	$19.4
1990	37	43	49	51	67	72	102
2000	16	18	21	22	29	31	44
2010	7	8	9	9	12	13	18
2020	3	3	3	4	5	5	7
2030	1	1	1	1	2	2	2
2040	0	0	0	0	0	0	0

reduces the value of benefits beyond a 50-year horizon to a negligible level.

Costs of the rehabilitation are the same as those presented in Table 5-1 for t_1 values $\leq$ 2040. For the extreme case of t_1=2090 the present value of costs drops to about \$4,000 and net benefits are -\$4,000. The strategy of postponing rehabilitation to the latest possible date is unaffected by the length of the planning horizon because of the small magnitude of benefits and the effect of the discount factor. Pushed to a logical conclusion the project should be put off indefinitely to the point where the discount factor reduces costs to zero; exactly the result we expect when there are no net welfare gains to be had from a project.

It is clear that the discount factor, $(1+r)^{-t}$, plays a major role in the optimal timing of a project. As the interest rate increases smaller weights are applied to future values of benefits and costs. Higher discount rates further diminish the already negligible benefits and simultaneously reduce the present value of the difference between costs and benefits.

A discount rate lower than 8.625 percent results in larger future benefits and lower interest during construction costs. At a zero percent discount rate benefits equal the total value of time saved in Table 5-1 and costs are constant at \$12.4 million as interest during construction cost goes to zero and future costs are not discounted. With a zero interest rate maximum net benefits of -\$11,938,000 are achieved with base-year construction. Costs no longer decline as rehabilitation is delayed but benefits do because they accrue over fewer and fewer years as the rehabilitation is postponed.

With a zero discount rate the project should be implemented as soon as possible in order to accrue as many benefits as possible. A longer planning horizon obviously enhances the economic feasibility of the project as undiscounted benefits increase for the additional years. Maximum benefits for the project with base year construction and a 100-year horizon are $1,310,000. This is a 19.5-fold increase over the level of benefits observed over a 50-year horizon with an 8.625 percent discount rate. This is a large increase in the relative and absolute level of benefits yet net benefits are still -$11.09 million. With a sufficiently long horizon the project could eventually be justified.

Variations in the assumed cost per tow-hour have no appreciable effect on the magnitude of benefits. Doubling, tripling or halving the hourly tow costs has no effect on the interpretation of the results. Such changes can be trivially incorporated and are not be considered further.

One of the weakest links in this analysis is the lack of quantitative information about the way lock capital deteriorates and its useful life. The analysis presented above assumes that rehabilitation makes the stock of lock capital as good as new. After rehabilitation the capital stock has an assumed remaining useful life of 150 years. If in fact rehabilitation does nothing to extend the remaining useful life of a structure but simply makes it operate more efficiently we can expect a different level of benefits. This is because the Kp of [illegible] above will take on different values depending on the value of the depreciation function (3) which in turn depends on the value of the age argument shown in equation (15) of Chapter 3. Table 5-3 differs from Table 5-1 only in that rehabilitation is assumed to have no effect on the remaining useful life of the capital stock. There are minimal differences in the benefits in the two tables for this particular project. As expected with no effect on the remaining life of lock capital benefits decrease. The reason for this difference is illustrated in Figure 5-4. In Figure 5-4(a) rehabilitation occurs in year t_1. Rehabilitation causes an increase in lock capital. If the rehabilitation does not increase the structure's useful life the higher level of capital is still fully depreciated by year 150. With an extended remaining life full depreciation is not complete until year t_1+150.

Figure 5-4(b) illustrates the nature of the effect of lock capital on transit time. The more lock capital in existence at a given point in time the less time it takes to transit a lock. Over the 50 year planning horizon the assumption of depreciation with an extended remaining life of the asset results in a lower mean transit time. This time savings is shown as the cross-hatched area in Figure 5-4(b).

It can be seen from the figure that the timing of the rehabilitation can affect the magnitude of the differences in lock capital, transit time and subsequently benefits. To illustrate this point Figure 5-5 presents a hypothetical alternative situation which varies the time at which t_1 occurs. Though the selection of t_1 can clearly make a difference in the relative size of the shaded area the effect of the discount function must always be born in mind. If t_1 in

TABLE 5-3
BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
NO CHANGE IN REMAINING USEFUL LIFE
($1000s)

ITEM	YEAR OF REHABILITATION 1900	2000	2010	2020	2030	2040
Total time saved hours	937	743	553	366	186	16
Total value of time saved	$428	$340	$253	$167	$85	$7
Present value of time saved	64	27	11	4	1	0
Present value of rehab costs	14540	7230	3160	1380	600	260
Net benefits	-14476	-7203	-3149	-1376	-599	-260

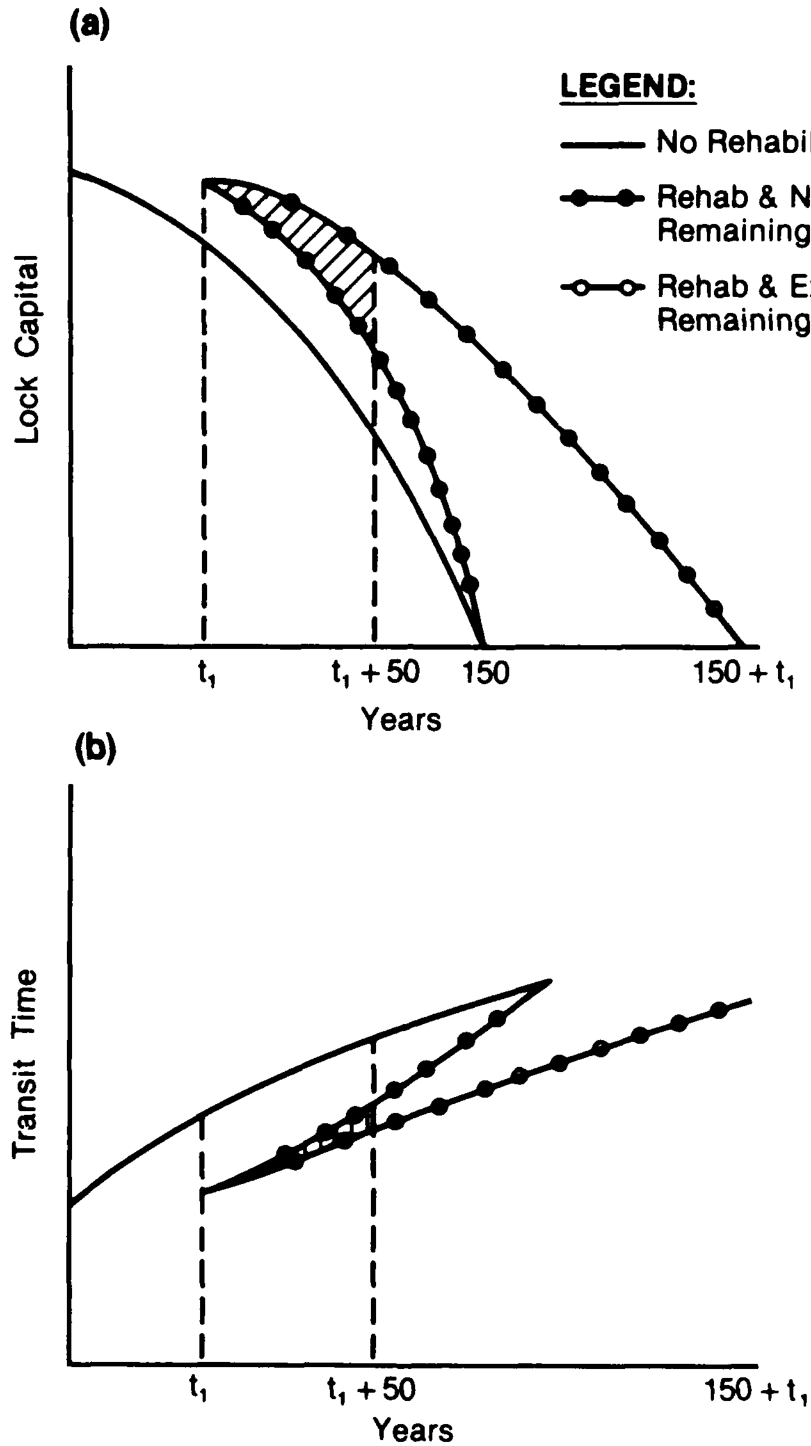


Figure 5-4
EFFECT OF EXTENDED ASSET LIFE

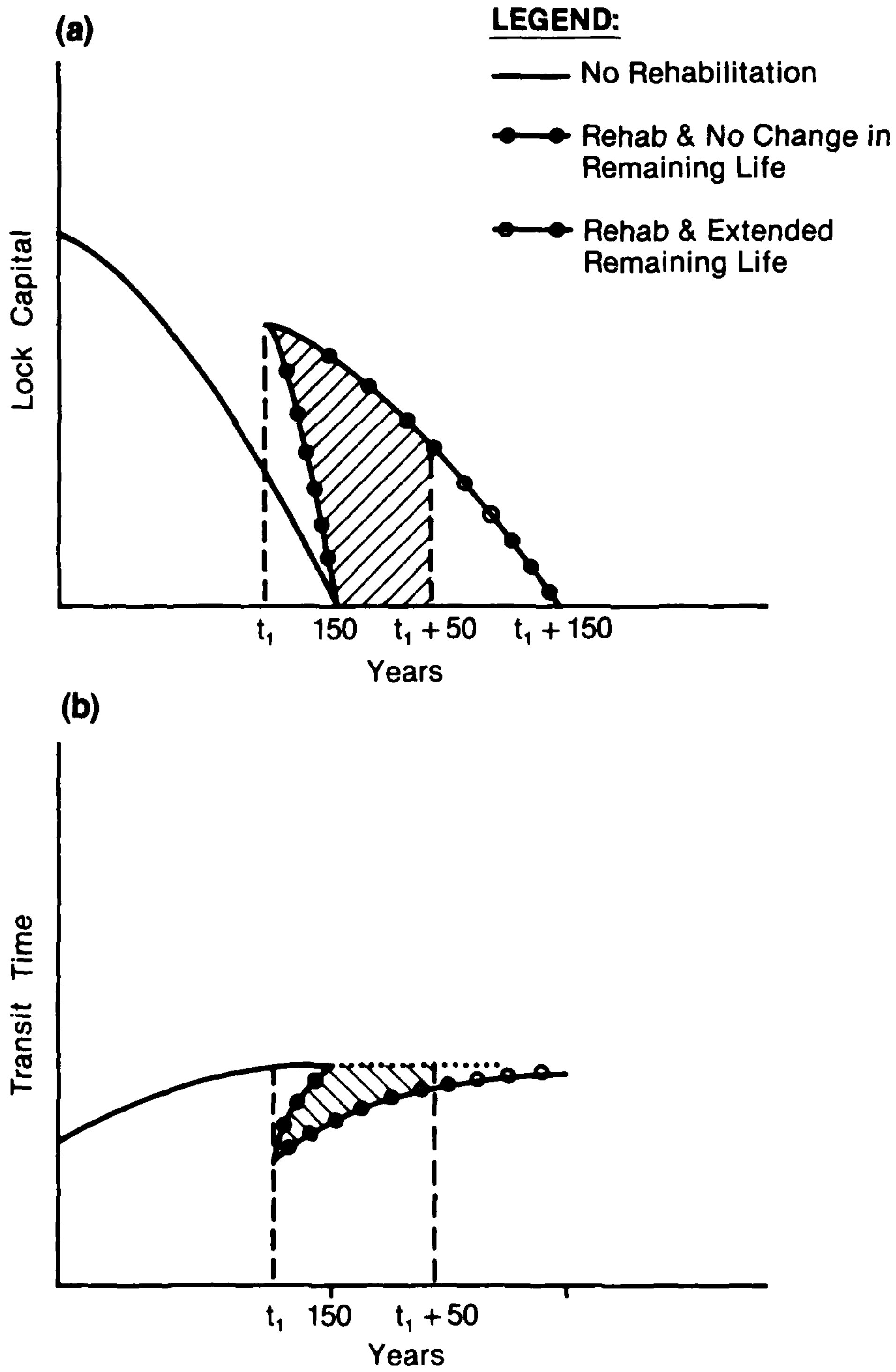


Figure 5-5
BENEFIT SENSITIVITY TO t_1

Figure 5-5 occurs in the distant future the discount function will give little weight to the value of the resultant areas under the demand curves. On the other hand the relative closeness of t_1 to the end of the structure's life could be because the structure is very old when t_1 is near the base year. In this case the discount function will have less effect on future flows of dollars. The position of t_1 could be the base year 1990 or some distant future date and the magnitude of benefits will vary accordingly.

A third and less satisfying possibility for depreciation of lock capital after rehabilitation is that the rehab capital has a useful life and depreciation path separate from the original capital stock. In such an event the original capital stock has a remaining life of 150 years less its age at the time of rehabilitation while the rehab capital has a remaining life of 150 years. This assumption leads to the results shown in Table 5-4.

Table 5-4 presents benefits for the $12.4 million project higher than those in the two previous tables, although there is no significant change in results or the conclusions drawn from them. Benefits differ because the previous analyses combine the existing capital stock with the rehabilitation stock and depreciate them. In Table 5-4 the stocks are depreciated separately and then combined. Because of the nonlinear depreciation function the latter technique leads to a higher estimate of the available capital stock during any given year which in turn leads to lower estimates of transit time and more benefits. This last depreciation pattern is considered far less feasible than the other two.

TABLE 5-4
BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
TWO CAPITAL STOCKS AND DEPRECIATION PATHS
($1000s)

ITEM	YEAR OF REHABILITATION 1990	2000	2010	2020	2030	2040
Total time saved hours	4682	3765	2848	1930	1011	18
Total value of time saved	$2140	$1721	$1301	$882	$462	$42
Present value of time saved	317	136	57	22	7	0
Present value of rehab costs	14540	7230	3160	1380	600	260
Net benefits	-14223	-7094	-3103	-1358	-593	-260

Table 5-5 summarizes the effect of assuming a 100-year useful life for the lock and dam on benefits and costs. All other assumptions such as 50-year planning horizon, interest rate, concave depreciation function, etc. are the same as in the initial presentation of Table 5-1.

The first result of a shorter asset life is that full depreciation occurs sooner, in this case 50 years sooner. With the concave depreciation function this means the relatively precipitous drop in the amount of lock capital available will occur sooner in the planning horizon. As a result, the amount of depreciation which occurs during the planning horizon is increased. That this is true can be seen in the doubling in the total amount of time saved between Tables 5-1 and 5-5.

When the value of the time savings are expressed as present values, however, the differences are no longer as dramatic. If the rapid drop in the depreciation function occurs far enough in the future the discount function will reduce the value of the changes to a relatively trivial difference in benefits. How far into the future the decline occurs depends on the life of the asset and its age at the beginning of the planning horizon. With a 100-year asset life and a lock that will be 50 years old in the base year 1990, the rapid depreciation of lock capital occurs near the end of the planning horizon. The value of the benefits of altering this depreciation pattern is minimized by the effect of the discount function.

In the case of L&D 13 the difference in the assumed asset life makes no difference to the results. There are net welfare losses and the project should not be undertaken. Net benefits are maximized, actually

TABLE 5-5
BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
100-YEAR USEFUL LIFE OF CAPITAL ASSETS
($1000s)

ITEM	YEAR OF REHABILITATION 1990	2000	2010	2020	2030	2040
Total time saved hours	2867	2678	2482	2275	2061	1839
Total value of time saved	$1310	$1224	$1134	$1040	$942	$840
Present value of time saved	68	30	13	6	3	1
Present value of rehab costs	14540	7230	3160	1380	600	260
Net benefits	-14472	-7200	-3147	-1374	-597	-259

net losses are minimized, in the last year of the planning horizon for every non-zero level of rehabilitation.

The difference in the total time saved and concomitantly in the undiscounted value of this savings with a shorter asset life is significant as long as the planning horizon is long enough to include the sharp decline of the depreciation function. Figure 5-5 illustrates this effect. For simplicity let t_1 represent both the base year and the year rehabilitation is completed. The planning horizon is given by t_1+50. T is the end of the asset life, T+50 is the end of the asset life after it has been rehabilitated. The cross-hatched area in Figure 5-5(a) shows a planning horizon for an asset rehabilitated relatively early in its life. The differences in available capital and, as a result, in transit time and benefits are small. In Figure 5-5(b) the cross-hatched area corresponds to rehabilitation relatively late in the asset's life. The potential benefits here are several magnitudes larger. The weights placed on these differences by the discount function determine the ultimate value of the benefits.

Two general points result from this analysis. Transit time savings are larger the older the lock is when rehabilitated. When a lock is near the end of its useful life rehabilitation produces the greatest improvement in mean transit times. If a lock is near the end of its useful life benefits are maximized when t_1 is closest to the base year. This is just another way of saying that benefits are larger the less they are discounted.

Up until now all results have relied on the assumption of a concave depreciation function. Table 5-6 presents a comparison of the present

TABLE 5-6
PRESENT VALUE BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
FOR SELECTED FUNCTIONAL FORMS OF LOCK CAPITAL
$1000s

YEAR REHAB COMPLETE	LOCK CAPITAL VARIABLE				
	$K^{.1}$	$K^{.3}$	$K^{.5}$	$K^{.7}$	$K^{.9}$
1990	$67	$59	$67	$64	$87
2000	29	25	29	27	37
2010	12	11	12	11	16
2020	5	4	5	4	6
2030	1	1	2	1	2
2040	0	0	0	0	0

value of net benefits for the $12.4 million rehabilitation plan at L&D 13 for selected functional forms of the lock capital variable.

The most significant result is that neither the absolute nor relative magnitudes of benefits are very sensitive to the transformation of lock capital. Costs for the project by year remain identical to those in Table 5-1

The square root transformation of lock capital henceforth designated K is the lock capital variable that has been used to this point. Table 5-7 presents benefit estimates for various lock capital variables based on different depreciation functions. Once again the relative and absolute magnitudes of benefits are not very sensitive to the choice of lock capital variable.

K67 and K50 are also concave functions like K but the rates of depreciation are 0.50 and 0.67 respectively, instead of 0.9866. The obvious result is that given a concave function the greater the rate of depreciation the larger the benefits. Though time savings show a significant increase benefits do not because of the effects of the discount function.

KGI represents capital decaying geometrically at a rate twice the reciprocal of the asset life. The differences in the value of lock capital productivity over the planning horizon is not very great when we compare concave and convex depreciation patterns with the same rate of decay.

KSL is a straight line depreciation path estimate of lock capital. It too suggests that for L&D 13 the depreciation pattern does not make a great deal of difference in the magnitude of benefits. The results for

TABLE 5-7
PRESENT VALUE BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
FOR SELECTED LOCK CAPITAL DEPRECIATION PATTERNS
$1000s
(TOTAL TIME SAVINGS IN HOURS)

YEAR REHAB	LOCK CAPITAL VARIABLE					
COMPLETE	K	K67	K50	KGI	KSL	KOHS
1990	$67	$83	$114	$92	$78	$67
	(1011)	(1468)	(1942)	(1239)	(1117)	(987)
2000	29	37	53	42	37	29
	(814)	(1205)	(1654)	(1087)	(1030)	(794)
2010	12	16	24	19	17	13
	(616)	(913)	(1303)	(896)	(869)	(620)
2020	5	7	10	8	7	6
	(416)	(607)	(903)	(661)	(641)	(426)
2030	2	2	3	3	2	3
	(217)	(304)	(474)	(378)	(359)	(232)
2040	0	0	0	0	0	1
	(19)	(25)	(40)	(37)	(34)	(39)

K and KGI would in fact be found clustered in a relatively narrow band around the straight line depreciation paths. Referring to Figure 5-4 this means that the area between the geometric decay and concave functions, which contains the straight line function, is relatively small given the low annual rate of decay. The results for K6[illegible] and K[illegible] indicate that as the function bends away from the straight line function, i.e., as the rate of decay increases, the differences in benefits become larger.

KOHS is the one-horse shay model of lock capital with no depreciation until the asset reaches the "predictable" end of its useful life at which time full and instantaneous depreciation occurs. KOHS results in benefits that are comparable to the benefits from the other depreciation assumptions.

Varying both the lock capital variable and the useful life of L&D 13 produces minimal increases in benefits. The results of this sensitivity analysis are shown in Table 5-8.

The analyses presented above have been carefully designed to vary one assumption at a time to examine the effect of different assumptions on the magnitude of mean lock performance improvement benefits for the rehabilitation plan recommended for L&D 13. Actual values have been used for the model's variables. One of these, age of the lock, has been of particular interest on several occasions. The following sensitivity analyses for the application of the model to L&D 13 will make hypothetical changes in selected lock characteristics beginning with age. The new lock age is arbitrarily set at 96, 50 years greater than the actual age. This is done in order to move that portion of the

TABLE 5-8
PRESENT VALUE BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
FOR SELECTED LOCK CAPITAL DEPRECIATION PATTERNS
AND A 100-YEAR ASSET LIFE
$1000s
(TOTAL TIME SAVINGS IN HOURS)

YEAR REHAB COMPLETE	LOCK CAPITAL VARIABLE					
	K	K67	K50	KGI	KSI	KOHS
1990	$75	$120	$133	$104	$201	$70
	(2166)	(3380)	(3535)	(1318)	(4115)	(1627)
2000	37	62	68	48	107	32
	(1952)	(2940)	(3055)	(1193)	(3794)	(1433)
2010	19	31	34	22	55	16
	(1717)	(2378)	(2449)	(1009)	(3271)	(1259)
2020	11	15	16	9	26	9
	(1446)	(1713)	(1748)	(756)	(2537)	(1065)
2030	6	8	6	3	10	6
	(1085)	(962)	(984)	(421)	(1563)	(871)
2040	0	1	0	0	1	2
	(88)	(190)	(100)	(18)	(165)	(252)

depreciation function in which capital stock deteriorates most rapidly into the planning horizon. Table 5-9 indicates that all other things equal rehabilitation of an older lock results in more benefits. K100 refers to a 100-year asset life.

The final sensitivity analysis is a hypothetical variation of the initial capital stock. The initial capital stock of $65.02 million has been varied by ± $30 million, an arbitrary and large figure. The results of this analysis are presented in Table 5-10. As expected from economic theory and the signs of the marginal products presented in Chapter 4 a $12.4 million rehabilitation has a positive but decreasing effect on output benefits as the initial capital stock is increased.

TABLE 5-9
PRESENT VALUE BENEFITS OF MEAN LOCK PERFORMANCE IMPROVEMENT
FOR 46 AND 96 YEAR OLD LOCKS
$1000s
(TOTAL TIME SAVINGS IN HOURS)

YEAR REHAB	46-YEARS OLD		96-YEARS OLD	
COMPLETE	K	K100	K	K100
1990	$67	$75	$79	$304
	(1011)	(2166)	(2292)	(4476)
2000	29	37	38	130
	(814)	(1952)	(2051)	(3602)
2010	12	19	20	54
	(616)	(1717)	(1802)	(2726)
2020	5	11	11	21
	(416)	(1446)	(1526)	(1848)
2030	2	6	6	7
	(217)	(1085)	(1135)	(969)
2040	0	0	0	0
	(19)	(88)	(92)	(88)

TABLE 5-10
PRESENT VALUE OF BENEFITS FOR MEAN LOCK PERFORMANCE
FOR SELECTED HYPOTHETICAL INITIAL CAPITAL VALUES
$1000s

(TOTAL TIME SAVINGS IN HOURS)

YEAR REHAB	INITIAL CAPITAL		
COMPLETE	$35.02 MILLION	$65.02 MILLION	$95.02 MILLION
1990	$88	$67	$56
	(1315)	(1011)	(857)
2000	38	29	24
	(1059)	(814)	(691)
2010	16	12	10
	(802)	(616)	(522)
2020	6	5	4
	(543)	(416)	(352)
2030	2	2	1
	(284)	(217)	(183)
2040	0	0	0
	(26)	(19)	(16)

CHAPTER 6

CONCLUSIONS

LOCK REHABILITATION

For the specific case of L&D 13 benefits from improvement in mean lockage performance are insignificant in magnitude. This is true for a wide variety of assumptions made about model parameters and variables. It may be that mean lock performance benefits will consistently prove to be trivial in magnitude. However, that has not yet been proven and there are some compelling reasons for further estimation of these benefits.

First, with transit times expressed as a function of lock capital the marginal costs of estimating these benefits for any rehabilitation study are now very small. The system of equations has been estimated and solution of the model is straightforward. The benefits thus estimated, no matter how small, are legitimate project benefits.

A second reason for not writing this category of benefits off completely on the basis of one application arises from some of the tendencies summarized in Chapter 5. The value of mean lock performance improvement will be relatively greater for some projects than for others. It is possible that under certain combinations of asset age, demand for lockages, depreciation pattern, etc. these benefits could become significant in magnitude.

The small magnitude of these benefits for L&D 13 and the likelihood of small benefits for most lock rehabilitations has an important implication for the economic analysis of lock rehabilitation alternatives. If the economic value of improved mean transit times pales alongside the costs of achieving them and such projects continue to be undertaken, then the nature and technique of estimating benefits currently used to justify the projects need to be carefully scrutinized.

Rehabilitation of L&D 13 cannot be economically justified on the basis of increased output resulting from the additional lock capital. The sole justification of the rehabilitation project offered by the Corps of Engineers rests on the assumption that rehabilitation will prevent failure of critical elements of the lock preventing catastrophic losses to shippers and more costly repairs. The assumed probability distributions which underlie the failure forecasts are extremely subjective.

The results of this analysis do nothing to ease the burden placed on the estimation of subjective catastrophe benefits to justify rehabilitation projects. If the assumed lock failures would not in fact occur without lock rehabilitation, a net welfare loss results from rehabilitation. With a ten year rehabilitation program of half a billion dollars the potential losses are not trivial.

The relatively small improvements in transit time which result from lock rehabilitation can be interpreted as an argument that there has been no sudden decay in lock capital's performance despite the system's advancing age. The sensitivity analyses indicate that such decay is possible, however, depending on the asset's useful life, age and depreciation function. A policy of major rehabilitation of inland waterway infrastructure cannot be justified on the argument that the productivity of the locks, measured in mean transit time, is declining. A major rehabilitation program will be economically justified only if the risk of lock failure without rehabilitation is high. That this risk is high for any lock has not been established empirically. Evaluation of the risk of lock failure remains a critical research need for a coherent and rational lock rehabilitation policy.

This analysis was hampered by the lack and quality of data available for estimating the quantity of lock capital. There are no data available that describe the physical characteristics or performance of the infrastructure. Answers to questions like how long locks last, how they deteriorate, what is the probability of lock failure are purely conjectural in the absence of such data.

PUBLIC INFRASTRUCTURE

The conclusions reached for L&D 13 in particular and lock rehabilitation in general may have some relevance for public infrastructure rehabilitation issues. First, the lack of data about physical characteristics of public infrastructure will lead to difficulties in measuring public infrastructure. Because of their public good characteristics markets for used public infrastructure assets do not exist and price data are unavailable. In the absence of useful life information it is difficult to estimate existing levels of lock capital by any of the commonly accepted price or quantity measures of capital.

Without reliable measures of public infrastructure capital it is not possible to estimate its contribution to national income accounts. Estimating reasonable production or cost relationships cannot be done, making partial equilibrium analysis of individual projects more difficult.

The hierarchical demand structure offered in this analysis is likely to be reasonable for many types of infrastructure involving the transportation of people, freight or other commodities. Improvements in the delivery of infrastructure services may often be negligible to the consumer/producer who makes economic choices at higher levels in the hierarchy. For example, rehabilitation of structural defects in a single bridge in a local commuter route may have absolutely no effect on the mean commuting time. The effect of rehabilitation on the delivery of infrastructure services and the benefits associated with these improvements may often be minor.

The partial equilibrium setting is the biggest drawback of this analysis. Analyzing public infrastructure components one at a time it may not be rational to rehabilitate or replace them. Stepping back and looking at the entire infrastructure system may lead to an entirely different conclusion.

Though the productivity of much infrastructure capital may not be declining noticeably there is a great deal of concern over the adequacy of the nation's infrastructure. Fear of the potential catastrophic effects of infrastructure failure motivate many public infrastructure policy initiatives. If the results of the lock analysis are generally applicable then perhaps it is not erosion of services that motivates interest in infrastructure problems as much as it is the perception that the reliability of the service is low or conversely the risk of service failure is high.

The safety-minded conservative bias of the engineering profession may, in the absence of empirical data, be leading to subjectively biased probability estimates of failure that distort the economic realities of the expected cost of infrastructure failure. We need more reliable methods for assessing the risk of infrastructure failure if we are to have rational public policies addressing infrastructure problems. More reliable empirical data on the life and deterioration of public infrastructure are needed to better determine the potential benefits and costs of improving mean performance and diminishing the probability of catastrophic failures. The "infrastructure adequacy problem" is an expensive one that will not go away anytime soon.

APPENDIX 1

THE DATA

INTRODUCTION

The U.S. Army Corps of Engineers' Lock Performance Monitoring System (PMS) was established in March, 1975 to collect data for systems analysis of the inland waterway. The data are collected at the locks and consist of information describing the traffic moving through the locks and certain physical aspects of the lockage.

THE PMS DATA

PMS data for the year 1984 were used in this analysis. This year was selected because complete data sets from most earlier years were not available. 1984 was the most recent calendar year of data available at the time this study was initiated. The year is considered to be more or less typical in terms of climate, tonnage and other critical factors for the system overall.

PMS data are collected by Corps personnel at the lock. The data are recorded on three separate forms by the lock operator. The first is the shift log which records identification variables such as lock, date, etc. and weather, pool level and surface condition variables. The second form is the lockage log which is completed for each vessel transiting the lock. This log contains lockage specific data such as lockage type, chamber used, number of cuts, times at which various procedures began and ended, etc. Stall data are also recorded on this log. The third form is the vessel log. This log contains flotilla specific data. The variables recorded include flotilla length and width, number of barges, tonnage, etc. The vessel captain usually provides the information needed for this log. All three logs are coordinated by a record number to keep the data grouped accurately.

Provisions are made for the collection of data for up to 218 variables. Data for only about 100 of these variables is available. Data for some variables such as tonnage by cargo type are not routinely collected. Other data such as vessel name and horsepower of the vessel are considered confidential and are unavailable for general use. In 1984 there were 671,176 records available. Corps Pamphlet 84-PM-1, "Overview of the Lock Performance Monitoring System", provides detailed descriptions of the data collected and the variables available from the raw data. When the data base was being built I did not know which variables would ultimately be important in the analysis. Because of the size of the data base and the time and expense involved in manipulating it it would not be feasible to reenter the raw data a second time to create additional variables. I made efforts to anticipate every conceivable variable which could be of interest. Variables were constructed so as to make the generation of additional variables as painless as possible. As a result far more variables were generated than were finally needed for the estimation of key relationships and solution of the model.

TRANSFORMATIONS AND PROBLEMS WITH PMS DATA

PMS data are collected for individual lockages. They do not explicitly contain values of variables such as the length of time between arrivals of tows, the amount of time it takes to complete a lockage for a tow, the length of the queue when a tow arrives, how much traffic a lock handles in a year, how many lock-related stalls occur, etc. These and other variable values are of considerable interest in this analysis.

The first task in the analysis was to create a usable data set from the raw data. This was done on a lock-by-lock basis, i.e., the 1984 raw data for one lock was transformed then the data for another lock was transformed, etc. The new data bases were created using the Statistical Analysis System (SAS) programming language. The transformations consist of the generation of new variables from existing ones, generation of interpretive variables from consecutive records, e.g., length of queue, and the use of means and annual sums for certain variables ,e.g., total number of stalls in a year or annual tonnage. Some of the transformations were lockage-specific; most were lock-specific, i. e.,they vary from lock-to-lock but not from record-to-record. Lockage specific data consist of 15,104 different records while lock specific data consist of 15,104 repetitions of 82 different values.

During the course of manipulating and analyzing the PMS data numerous problems were discovered. While it is not the purpose of this paper to provide a critique of the quality of PMS data several of these problems will be described because they have some impact on the final form of the analysis.

The most striking problem presented by the data base are the differences in the data collected at each lock. The descriptions of the PMS data base promise more variables than they consistently deliver. For example, data on the type of lockage, i.e., entries for double cuts, setovers, knockouts, etc. were not available. For some locks current and weather conditions are always recorded conscientiously while for others they are not. Data editing programs of the Corps are designed to insure that entries are consistent with the allowable possibilities. It appears that a zero entry is automatic for many descriptive variables at some locks. As a result a reliable subset of variables describing the type of lockage, current and weather conditions--which the engineering literature suggests are important determinants of transit time -- were for the most part unavailable.

The apparent fact that there are differences in the data collection effort from one lock to the next remains a specter throughout the analysis when discrete valued dummy variables are used. The uniformity of these data can never be certain. Fortunately the quality of the more quantitative variables is much more even and dependable with one major exception. Data for stalls seem to be somewhat questionable.

Generation of the transformed variables required very detailed study of the raw data in general and the stall data entries in particular. The most common problems incurred with stall data seemed to be inconsistencies in recording the beginning and ending time of the stall. In some cases the start of the stall is recorded but the ending is not. In such cases the end of a stall is often recorded at the time monthly data bases are updated. The ending time is often little more than a guess. This results in a misstatement of the length of the particular stall and of the mean length of stalls. Some districts arbitrarily fix the unrecorded end of a stall at the end of the month. When this happens stall lengths may be overstated.

A related problem arises when the same stall is recorded more than once. For example, the data contain at least one instance where a stall of several weeks has three separate starting times and one common ending time. This overstates the number of stalls and has an a priori indeterminate effect on the mean length of stalls. Early efforts to correct these errors through district personnel quickly proved this is an impossible task. The quality of data available on a specific lock stall a year or more ago is negligible. Although it is in theory possible to correct such errors the cost of discovering and correcting them is astronomical. The only real options are to ignore the stall data completely or to hope the problems mentioned are not too severe. This analysis has opted for the second alternative.

A third significant problem with the data has been discussed in Louis Berger & Associates' 1981 report on PMS for the Corps. The problem is that tonnage values reported in the PMS data base do not match official estimates of tonnage for the individual locks contained in the Corps' "Waterborne Commerce Statistics" (WCS). PMS is not intended as an official record of actual tonnage. PMS tonnage is reported by the vessel captain. Waterborne Commerce data is taken from the bills of lading.

Vessel captains may not be well informed as to the volume and nature of their cargo and PMS data on tonnage may be inaccurately reported. A 1979 Battelle Corporation study compared Waterborne Commerce and PMS tonnage records on the Ohio River. The data sources differed by an average of 20 percent at each lock. PMS data were found to more accurately reflect actual cargo flow despite the potential inaccuracies in reporting tonnage. Inaccurate bills of lading used by WCS and the PMS system's ability to check data at each lock the cargo traverses may offset the disadvantages of the PMS data base estimates of tonnage.

This discrepancy in tonnage estimates is of some concern. If the method of recording PMS tonnage data varies systematically in some way across the various locks, parameter estimates for this variable will reflect the built in data collection bias. The fact that the locks used in this analysis are primarily the mainstream locks with relatively homogeneous traffic, users and management coupled with previous awareness of this problem and efforts to standardize PMS data collection methods lead to the assumption that this data collection bias is minimized.

OTHER DATA SOURCES

The PMS data base did not include values for all the variables of interest in this analysis. Though PMS was the basis for data for individual lockages and values of certain annual variables it contains no data on individual lock characteristics. These lock-specific data were obtained from a variety of sources.

Lock capital is an important enough variable to merit a separate discussion in Chapter 3. It was not possible to obtain good estimates of the construction costs for all locks. This was the determining factor in selecting those locks which were included in the final estimation data sample. Because lock capital is the state variable it is necessary to have a reliable estimate of the amount of lock capital in order to estimate the effects of a change in lock capital on any variables of interest. Appendix 2 contains estimates of lock capital in 1984 for the 78 locks in the sample.

There are two types of locks for which reliable cost estimates were not available. Most common is the lock where the entire project has never been completed. Though the lock and dam are functioning there may be elements of the project that were not completed. As a result construction cost estimates include both actual costs incurred and estimated costs to complete the project. Generally the records on the construction costs of these projects are too old and of insufficient detail to separate actual from projected expenses.

The other class of excluded locks consists of those locks with no construction cost history or with construction dates so old that reasonable deflating of the costs is impossible. These locks tend to have been built at the end of the 19th century and/or were donated to the Federal government after construction. These projects tend to be the smaller locks and dams on the less busy waterways.

In addition to lock capital there are numerous variables concerning lock characteristics of interest. These variables include the physical specifications of the lock and dam including chamber width and length, age, dam length, type of filling system, number of chambers, etc. These data were obtained from the same annual reports and project map books referenced above. An additional source of information was the "Inland Navigation Systems Analysis Physical Characteristics of the Inland Waterways, Table A: Locks".

During the course of the investigation several engineers suggested that conditions in the approaches to the locks were very important factors in determining service time. To try to capture this effect several proxy variables were defined including the length of upper and lower approaches and approach walls and the number of navigation accidents at the lock. A Coast

Guard data base containing accident information is under preparation but was not available for use in this analysis. In its place the number of impacts, i.e., the number of times the lock has been damaged by being struck by a tow, was used. These data were obtained from the Corps' Repair, Evaluation, Maintenance and Rehabilitation, Research Program (REMR) data base which has been compiled by the Corps' Waterways Experiment Station.

Substantial efforts were made to obtain or generate operation and maintenance expenditure variables. These efforts failed due to lack of reliable data. In the absence of such indicators indices of lock capital condition other than age were investigated. The REMR data base provided two such potential indices. One was the total number of deficiencies recorded during routine inspections over the period 1965-1983 the other was the number of serious deficiencies recorded. Fewer serious deficiencies implies better conditions. More total deficiencies could mean poorer conditions at the lock or a more exacting inspection regime which could indicate higher maintenance standards and better conditions if there are no serious deficiencies.

APPENDIX 2

LOCK CAPITAL

Locks are identified by river code and lock number. Appendix 5 contains a complete list of the lock names. Definitions of the lock variables are provided at the end of this appendix.

ESTIMATES OF LOCK CAPITAL
MILLIONS OF 1984 DOLLARS

LOCK	K987150	K98100	K50150	K50100	K67150	K67100
MI01	95.92	94.18	85.46	77.76	88.48	81.96
MI02	39.21	38.59	30.83	24.89	33.32	28.47
MI03	49.99	49.44	41.17	35.26	43.88	39.25
MI04	51.08	50.43	41.47	34.72	44.31	39.03
MI05	53.35	53.12	43.21	36.27	53.12	46.28
MI55	47.78	47.20	38.91	32.89	41.61	36.85
MI06	42.20	41.69	34.37	29.05	36.75	32.55
MI07	56.67	56.02	46.42	39.50	41.09	23.69
MI08	61.63	60.92	50.48	42.95	53.89	47.96
MI09	66.53	66.32	54.79	46.92	58.39	52.23
MI10	48.29	48.14	39.33	33.25	42.06	37.24
MI13	64.65	63.93	53.24	45.60	56.74	50.75
MI19	58.31	57.58	50.48	45.12	52.86	48.51
MI26	117.09	115.79	96.43	82.58	102.76	91.92
IL01	25.77	25.67	23.58	22.31	24.30	23.39
IL02	25.43	25.08	20.36	16.84	21.88	19.06
IL03	52.40	51.76	42.68	36.07	45.63	40.41
IL04	46.24	45.60	39.79	34.65	37.02	30.62
IL05	36.37	36.24	29.11	24.08	31.29	27.25
IL06	52.70	51.97	42.18	34.89	45.34	39.49
IL07	29.14	28.83	24.13	20.79	25.67	23.07
IL08	24.37	24.12	20.18	17.39	21.47	19.30
AG42	17.91	17.68	14.42	12.02	15.48	13.56
AG43	19.06	18.80	15.34	12.79	16.46	14.42
AG44	15.56	15.28	12.00	9.43	13.04	10.91
AG45	17.67	17.35	13.63	10.71	14.81	12.39
AG46	13.73	13.50	10.66	8.46	11.57	9.75
AG47	13.37	13.16	10.51	8.49	11.36	9.71
AG48	28.75	28.31	22.74	18.51	24.53	21.10
AG49	21.64	21.40	17.82	15.26	18.99	16.99
GB21	19.00	17.82	20.99	20.89	19.66	18.79
GB22	17.78	17.69	15.99	14.93	16.57	15.80
MN22	67.77	67.39	60.16	55.53	62.62	59.22
MN24	43.31	39.29	49.19	48.79	45.09	41.89
MN25	106.55	106.23	99.13	94.90	101.60	98.62
MN27	24.42	24.31	18.60	14.32	20.29	16.70
MN28	26.02	22.10	31.62	31.21	27.70	24.49
MN29	37.90	37.65	33.18	30.25	34.69	32.51
MN30	46.33	46.14	42.23	39.81	43.57	41.85
MN31	89.09	88.83	82.89	79.35	84.96	82.47
OH02	31.34	30.83	24.49	19.60	26.51	22.50
OH04	133.74	133.20	121.90	114.93	125.79	120.80
OH05	172.93	172.54	163.44	158.14	166.63	162.96
OH71	209.94	209.61	201.41	196.76	204.32	201.13
OH72	193.22	192.91	185.38	181.09	188.04	185.11
OH21	237.16	236.63	224.15	216.88	228.53	223.48
OH22	205.48	205.12	196.41	191.43	199.48	196.06
OH23	89.37	88.33	73.20	62.28	78.13	69.55

OH24	210.57	209.72	191.93	180.96	198.05	190.20
OH25	272.79	271.95	251.76	239.61	258.73	250.12
OH41	228.15	227.42	211.42	201.81	216.97	210.19
OH75	237.22	236.84	227.59	222.33	230.87	227.26
OH76	176.73	176.65	171.41	168.55	173.23	171.29
OH77	169.50	169.37	164.39	161.65	166.14	164.39
BW01	78.20	77.98	73.05	70.13	74.77	72.72
BW02	65.87	65.65	60.80	57.86	62.48	60.40
BW03	49.27	49.10	45.47	43.28	46.73	45.18
BW04	38.36	37.97	31.94	27.69	33.97	30.63
BW05	80.83	80.67	76.69	74.39	78.09	76.50
GI01	51.52	51.33	47.35	44.93	48.73	47.01
GI02	18.27	18.16	16.14	14.84	16.82	15.87
GI03	78.69	76.98	59.13	44.55	64.75	52.36
GI04	19.31	19.22	17.38	16.22	18.01	17.17
GI05	18.15	17.92	14.70	12.33	15.74	13.86
GI06	11.57	11.51	10.32	9.56	10.73	10.17
GI07	3.33	3.31	2.70	2.25	2.90	2.54
GI08	9.20	9.15	8.06	7.35	8.43	7.90
MK10	242.42	241.92	229.99	223.09	234.18	229.41
MK11	246.33	245.82	233.71	226.69	237.96	233.11
MK21	83.27	83.11	79.30	77.10	80.64	79.13
MK22	258.49	258.00	246.17	239.36	250.34	245.64
MK23	228.86	228.43	217.95	211.92	221.64	217.49
MK24	86.41	86.25	56.65	32.36	83.69	82.12
MK25	121.23	121.14	115.45	112.25	117.40	115.20
MK01	122.65	122.35	115.47	111.44	117.88	115.07
MK02	125.13	124.84	118.26	114.42	120.57	117.91
MK03	103.20	102.97	97.54	94.37	99.44	97.25
MK04	124.70	124.42	117.85	114.03	120.16	117.50
MK05	90.37	90.17	85.41	82.64	87.08	85.16
MK06	191.28	190.85	115.93	112.17	184.32	180.25
MK07	95.10	94.91	90.23	87.52	91.87	90.00
MK08	176.93	176.57	167.86	162.82	170.92	167.44
MK09	98.88	98.67	93.81	90.99	95.52	93.57
CU22	118.83	118.35	108.31	102.12	111.76	107.33
CU24	201.78	200.92	183.13	172.10	189.24	181.31
KA01	64.47	64.26	52.80	44.93	56.36	50.17
KA02	44.20	43.62	35.59	29.66	38.19	33.45
KA03	38.62	38.11	33.36	29.23	31.10	25.91

LOCK	K84	KSL150	KSL100	KGI150	KGI100
MI01	96.28	78.86	70.16	71.79	64.85
MI02	39.50	25.28	18.17	19.13	13.27
MI03	50.28	34.86	27.15	27.12	19.85
MI04	51.40	34.61	26.21	26.63	19.10
MI05	53.69	36.15	27.38	27.81	19.95
MI55	48.07	32.69	25.00	25.24	18.23
MI06	42.46	28.87	22.08	22.29	16.10
MI07	57.01	39.15	30.22	30.34	22.06
MI08	62.00	42.57	32.86	32.99	23.99
MI09	66.91	46.39	36.13	36.09	26.42
MI10	48.59	33.04	25.27	25.51	18.42
MI13	65.02	45.08	35.11	35.07	25.67
MI19	58.58	44.81	37.95	37.38	30.22
MI26	117.76	81.65	63.59	63.51	46.49
IL01	25.83	21.70	19.63	18.72	15.91
IL02	25.60	16.90	12.54	12.91	9.14
IL03	52.72	35.85	27.41	27.68	19.99
IL04	46.55	30.72	22.81	23.48	16.61
IL05	36.61	24.16	17.94	18.46	13.07
IL06	53.05	35.01	25.99	26.75	18.93
IL07	29.30	20.51	16.12	16.02	11.80
IL08	24.51	17.16	13.48	13.40	9.87
AG42	18.03	12.02	9.02	9.22	6.57
AG43	19.18	12.79	9.59	9.80	6.98
AG44	15.68	9.72	6.74	7.30	4.96
AG45	17.81	11.04	7.66	8.29	5.63
AG46	13.84	8.67	6.09	6.53	4.46
AG47	13.47	8.62	6.20	6.52	4.52
AG48	28.95	18.72	13.61	14.21	9.92
AG49	21.76	15.09	11.75	11.74	8.59
GB21	21.05	17.33	15.47	14.77	12.37
GB22	17.83	14.50	12.84	12.24	10.13
MN22	68.00	53.95	46.92	31.00	20.45
MN24	49.38	39.18	34.08	34.09	29.23
MN25	106.76	92.53	85.41	81.62	71.27
MN27	24.63	14.94	10.10	11.16	7.48
MN28	31.81	22.22	17.44	17.76	13.48
MN29	38.04	29.42	25.11	24.10	19.14
MN30	46.45	38.71	34.84	33.21	28.03
MN31	89.27	77.37	71.42	68.25	59.60
OH02	31.58	20.00	14.21	15.09	10.40
OH04	134.09	111.74	100.57	95.87	80.92
OH05	173.20	154.73	145.49	139.73	125.36
OH71	210.18	193.37	184.96	178.91	164.93
OH72	193.44	177.96	170.23	164.66	151.80
OH21	237.53	212.19	199.53	191.62	171.92
OH22	205.73	187.90	178.99	172.79	158.21
OH23	89.90	61.73	47.65	47.84	34.78
OH24	211.12	175.93	158.34	150.94	127.40
OH25	273.40	233.30	213.25	203.49	175.30
OH41	228.63	196.62	180.62	172.47	149.58

OH75	237.49	218.49	208.99	202.16	186.36
OH76	176.88	166.27	160.96	156.75	147.47
OH77	169.64	159.46	154.37	150.34	141.44
BW01	78.35	68.43	63.46	60.71	53.37
BW02	66.02	56.34	51.50	49.14	42.33
BW03	49.38	42.14	38.52	36.75	31.66
BW04	38.57	27.26	21.60	21.37	15.86
BW05	80.95	72.86	68.81	66.19	59.79
GI01	51.64	43.72	39.76	37.92	32.45
GI02	18.33	14.30	12.28	11.93	9.60
GI03	79.39	47.10	30.96	35.01	23.15
GI04	19.37	15.75	13.95	13.30	11.00
GI05	18.26	12.30	9.31	9.46	6.79
GI06	11.61	9.29	8.13	7.76	6.33
GI07	3.38	2.25	1.69	1.73	1.23
GI08	9.24	7.15	6.10	5.85	4.65
MK10	242.77	218.49	206.35	198.50	179.30
MK11	246.69	222.02	209.69	201.70	182.20
MK21	83.38	75.60	71.71	69.10	62.84
MK22	258.84	234.68	222.60	214.50	195.07
MK23	229.17	207.78	197.09	189.91	172.71
MK24	86.53	78.45	74.42	71.71	65.21
MK25	121.39	110.06	104.40	100.59	91.48
MK01	122.85	108.93	101.97	97.79	87.14
MK02	125.32	111.95	105.27	101.10	90.71
MK03	103.36	92.33	86.82	83.38	74.81
MK04	124.89	111.57	104.91	100.75	90.40
MK05	90.51	80.86	76.03	73.02	65.51
MK06	191.58	171.14	160.93	154.55	138.67
MK07	95.24	85.72	80.95	77.87	70.34
MK08	177.19	159.47	150.61	144.88	130.87
MK09	99.02	89.12	84.17	80.96	73.13
CU22	119.14	99.28	89.36	85.18	71.90
CU24	202.33	167.26	149.72	142.72	119.66
KA01	64.85	44.53	34.37	34.51	25.09
KA02	44.49	29.66	22.25	22.74	16.20
KA03	38.87	25.91	19.44	19.87	14.16

K is the initial level of capital in the functions below.

K987150=K*((150-age)/(150-.98666*age))

K98100 K*((100-age)/(100-.98*age))

K50150 K*((150-age)/(150-.5*age))

K50100 K*((100-age)/(100-.5*age))

K67150 K*((150-age)/(150-.67*age))

K67100 K*((100-age)/(100-.67*age))

K84 K is constant for 150 years and zero thereafter. Subsequently renamed K84150 and supplemmented by K84100.

KSL150 Straight line depreciation w/ 150-year service life.

KSL100 Straight line depreciation w/ 100-year service life.

KGI150 $(1-.01333)^{-t}$, t=1, ..., 150

KGI100 $(1-.02)^{-t}$, t=1, ..., 100

APPENDIX 3

EXPONENTIAL DISTRIBUTION HYPOTHESIS TESTING

Queuing theory assumes arrival rates are Poisson distributed and service times are exponentially distributed. This is equivalent to assuming that the time between arrivals and the service times both have a negative exponential distribution. These latter assumptions were tested on both an annual and a seasonal basis for the 78 locks in the data sample.

The hypothesized distribution was tested for annual and seasonal inter-arrival periods and service times. The non-parametric Kolmogorov-Smirnov one sample statistic was used to test the hypotheses. The empirical distribution function is defined by:

$$(1) \quad F_n(X)=k/n \qquad X_i \leq X \leq X_{i+1}$$

where k is the number of observations not greater than X.

The cumulative distribution function for a negative exponential density function is defined as:

$$(2) \quad F(X)=1-e^{-aX}$$

where a is the inverse of the mean of the variable of interest.

With tests for four seasons and the year for each lock there were 390 separate tests of the hypothesized negative exponential distribution. In every case, the Kolmogorov-Smirnov statistic exceeded the critical value for rejecting the null hypothesis that the empirical and hypothetical distributions were not significantly different. The assumption of Poisson distributed arrivals and exponential service times do not seem reasonable.

As a result of the findings of this analysis it was decided that parametric relationships for queue size, transit time, etc. found in the queuing theory literature would not be used. During the literature review for this research it appeared that it is a fairly common practice for the extensive and sophisticated models used by the Corps of Engineers to rely on the assumptions of Poisson distributed arrivals and negative exponential service times. If in fact these models rely on simple annual or quarterly distributions then the sensitivity of the results to such a maintained hypothesis need to be established. In light of the results obtained above it appears advisable for the users of these models to establish the validity of their assumptions.

APPENDIX 4

DEVELOPMENT OF THE ESTIMATION MODEL

THE MODEL

This appendix provides some brief but useful details on the development of the estimation model. The material is significant for the insight it lends to understanding the final form of the model and for the negative results obtained in some of the experimentation.

From the beginning of this research an interest of the sponsor and a goal of the analysis was to shed some light on the nature and causes of lock-related stalls. The original intention was to investigate relationships that would explain the length of a lock-related stall. The initial formulation of the model considered total transit time as the identity:

(1)Transit time=service time+time in queue+time delayed by a lock-related stall+time delayed by other stalls

where all the variables are lockage specific.

Such a model could be built from a system of equations developed in the manner presented in Chapter 4. Each of the variables in (1) would be an endogenous variable. Relationships of particular interest in the identity include:

(2)Length of a lock-related stall=f(lock capital, other exogenous factors)

(3)Length of other stall=g(lock capital, other exogenous factors)

Empirically supportable relationships between the dependent variables of (2) and (3) and any combinations of the independent variables that engineering science and experience with lock operations would suggest explain the length of a lock-related stall could not be found. For the most part parameter estimates were not statistically distinguishable from zero. Unexpected parameter signs were also frequently observed.

After all the reasonable possibilities for the form of the models had been estimated with no significant results, the data were mined. Using SAS's stepwise regression routine the length of a lock-related stall was regressed against 44 variables. The maximum R-square for a model with 44 variables and the experimental data set of 3,783 observations was .013. Results for the length of other stalls were not much better. The same variable set and data base led to a maximum R-square of .041.

A sample data set consisting entirely of stall event observations was also used to try to gain some insight into the models of equations (2) and (3). The results were essentially unchanged. There are no statistically significant relationships of any explanatory value to be had from the 1984 data. Additional research with a time series data base for a single lock may be fruitful in the future when the historical data base is a little larger. For lack of empirically significant results for the relationships in (2) and (3) the identity model of (1) was abandoned.

These negative results led to investigation of a different specification of the relationship between transit time and stalls. Instead of trying to estimate the expected length of a lock related stall for any lockage the cumulative annual length of lock related stalls and the annual number of all stall events were tested. The relationship of particular interest was the effect of lock capital on the endogenous variables: 1) annual downtime due to lock-related stalls and 2) annual number of stalls. The hypotheses were that as lock capital decreases the downtime at the lock increases and that the number of stalls also increased with a decrease in capital stock.

The data for this analysis were lock specific annual values and lock characteristics. There were 78 observations in the data set. An empirically significant causative effect of lock capital on the two endogenous stall variables could not be found. In the absence of a significant effect for the policy variable the stall variables were treated as exogenous in the model developed in Chapter 4.

DEPENDENT VARIABLE FORM

Various forms of the dependent variables were experimented with during the development of the model. Transit time per ton and transit time per various standard units of measure were tried. These measures did not work as well because regardless of the choice of the standard measure there was a significant number of observations which took zero values for the standard measure. Division by zero results in a missing value and loss of information about some type of lockage. Rather than systematically exclude any class of lockages the variable transit time was used. Similarly, various forms of the other dependent variable were tried and found lacking. Service time is better than service rate. Queue length measured in tows is superior to queue lengths measured in barges, tonnage or other values.

INDEPENDENT VARIABLES

The initial formulations of the model included variables which seemed to be the most obvious choices for important variables. Dam length, for example, seemed to be an obvious value to control because they range from 0 to 11,490 feet. In fact this variable did not improve the model significantly in any of its forms. There were numerous other variables similarly selected that do not appear in the final model. The various forms of the model and variables within the model tested are far too numerous to summarize in a practical way. Neither is it possible to explain why all or even some of the more "obvious" choices did not yield more predictable results.

A number of standardized independent variables which do not appear in the final results were tried during model building. For example, standardized barge units were created by dividing tow length times tow width by the area of a standard size barge. Tonnage per standard barge, barges per personnel working the lock, and individual lockage performance as a percent of the annual average performance for measures like exit, chambering time, etc. are but a few examples of the many transformations tried and rejected as inferior to the variables finally selected.

The experimental construction of the model was a thoughtful one. Relationships between and among variables suggested by queuing theory, engineering and production literature, field experience and Corps experts, and the various publications of the "National Waterways Study" guided the model building. Sample statistics and correlations were also studied to find supportable links between variables. If an obvious variable appears to have been omitted from the final model it is safe to assume that it most likely was tried and found wanting for some reason.

APPENDIX 5

LOCK NAME CODES

Following is a list of the names of each of the locks in the data sample and listed in Appendix 2. Throughout the anlysis locks were referred to by a four-digit alphanumeric code. The first two digits were from the river code and are letters. The last two digits are the number of the lock which is listed under lock code. Thus AT11 is the Berwick Lock (11) on the Atchafalya River (AT). The list of river and lock codes is excerpted from the PMS user's guide.

LOCK CODE IDENTIFICATION

LOCK CODE	RIVER NAME	LOCK NAME
MI01	Mississippi	Lock & Dam 1
MI02	Mississippi	Lock & Dam 2
MI03	Mississippi	Lock & Dam 3
MI04	Mississippi	Lock & Dam 4
MI05	Mississippi	Lock & Dam 5
MI55	Mississippi	Lock & Dam 5A
MI06	Mississippi	Lock & Dam 6
MI07	Mississippi	Lock & Dam 7
MI08	Mississippi	Lock & Dam 8
MI09	Mississippi	Lock & Dam 9
MI10	Mississippi	Lock & Dam 10
MI13	Mississippi	Lock & Dam 13
MI19	Mississippi	Lock & Dam 19
MI26	Mississippi	Lock & Dam 26
IL01	Illinois	Thomas J. O'Brien
IL02	Illinois	Lockport
IL03	Illinois	Brandon Road
IL04	Illinois	Dresden Island
IL05	Illinois	Marseilles
IL06	Illinois	Starved Rock
IL07	Illinois	Peoria
IL08	Illinois	LaGrange
AG42	Allegheny	Lock & Dam 2
AG43	Allegheny	Lock & Dam 3
AG44	Allegheny	Lock & Dam 4
AG45	Allegheny	Lock & Dam 5
AG46	Allegheny	Lock & Dam 6
AG47	Allegheny	Lock & Dam 7
AG48	Allegheny	Lock & Dam 8
GB21	Green	Lock & Dam 1
GB22	Green	Lock & Dam 2
MN22	Monongahela	Lock & Dam 2
MN24	Monongahela	Lock & Dam 4
MN25	Monongahela	Maxwell
MN27	Monongahela	Lock & Dam 7
MN28	Monongahela	Lock & Dam 8
MN29	Monongahela	Morgantown
MN30	Monongahela	Hildebrand
MN31	Monongahela	Opekiska
OH02	Ohio	Dashields
OH03	Ohio	Montgomery
OH04	Ohio	New Cumberland
OH05	Ohio	Pike Island
OH71	Ohio	Hannibal
OH72	Ohio	Willow Island

LOCK CODE	RIVER NAME	LOCK NAME
OH21	Ohio	Belleville
OH22	Ohio	Racine
OH23	Ohio	Gallipolis
OH24	Ohio	Greenup
OH25	Ohio	Maxwell
OH41	Ohio	Markland
OH75	Ohio	Cannelton
OH76	Ohio	Newburgh
OH77	Ohio	Uniontown
BW01	Black Warrior & Tombigbee	Coffeeville
BW02	Black Warrior & Tombigbee	Demopolis
BW03	Black Warrior & Tombigbee	Warrior
BW04	Black Warrior & Tombigbee	William Bacon Oliver
BW05	Black Warrior & Tombigbee	Holt
GI01	Gulf Intracoastal Waterway	Port Allen
GI02	Gulf Intracoastal Waterway	Bayou Sorrel
GI03	Gulf Intracoastal Waterway	Inner Harbor Navigation Canal
GI04	Gulf Intracoastal Waterway	Algiers
GI05	Gulf Intracoastal Waterway	Harvey
GI06	Gulf Intracoastal Waterway	Bayou Boeuf
GI07	Gulf Intracoastal Waterway	Vermilion
GI08	Gulf Intracoastal Waterway	Calcasieu
MK10	McClellan Kerr Arkansas	Dardanelle
MK11	McClellan Kerr Arkansas	Ozark
MK21	McClellan Kerr Arkansas	W. D. Mayo
MK22	McClellan Kerr Arkansas	Robert S. Kerr
MK23	McClellan Kerr Arkansas	Webber Falls
MK24	McClellan Kerr Arkansas	Chouteau
MK25	McClellan Kerr Arkansas	Newt Graham
MK01	McClellan Kerr Arkansas	Norrell
MK02	McClellan Kerr Arkansas	Lock & Dam 2
MK03	McClellan Kerr Arkansas	Lock & Dam 3
MK04	McClellan Kerr Arkansas	Lock & Dam 4
MK05	McClellan Kerr Arkansas	Lock & Dam 5
MK06	McClellan Kerr Arkansas	David D. Terry
MK07	McClellan Kerr Arkansas	Murray
MK08	McClellan Kerr Arkansas	Toad Suck Ferry
MK09	McClellan Kerr Arkansas	Lock & Dam 9
CU22	Cumberland	Cheatham
CU24	Cumberland	Old Hickory
KA01	Kanawha	Winfield
KA02	Kanawha	Marmet
KA03	Kanawha	London

BIBLIOGRAPHY

Aigner, D. J. and S. P. Chu, "On Estimating the Industry Production Function". American Economic Review. (1968): pp.826-839.

Amemiya, T., "Regression Analysis When the Dependent Variable is Truncated Normal." Econometrica. Vol. 42 (1973): pp.999-1012.

American Waterway Operators. Big Load Afloat. Washington D. C.: American Waterway Operators, 1973.

Arrow, K. J. and Kurz. Public Investment, the Rate of Return and Optimal Fiscal Policy. Baltimore: Johns Hopkins University Press, 1970.

Barta, Thomas J. "Bottlenecks Hindering Productivity in the Water Transportation Industry." Transportation Research Forum (1972).

Bazaraa, Mokhtar S. and C. M. Shetty. Nonlinear Programming Theory and Algorithms. New York: John Wiley & Sons, 1979.

Beach, E. F. "A Measure of Physical Capital." The Review of Economic Statistics. Vol. 2. (1938).

Beattie, Bruce R. and C. Robert Taylor. The Economics of Production. New York John Wiley & Sons, 1985.

Bellman, Richard and Robert Kalaba. Dynamic Programming and Modern Control Theory. New York: Academic Press, 1965.

Bellman, Richard , Kenneth L. Cooke and Jo Ann Lockett. Algorithms Graphs and Computers. New York: Academic Press, 1970.

Benavie, A. "The Economics of the Maximum Principle." Western Economics Journal (December 1970): pp. 426-430.

Blackwell, Richard B. "Toward Improved Cost Data for Inland Waterway Transportation." Transportation Research Forum (1964).

Bliss, C. J. Capital Theory and the Distribution of Income. Amsterdam: North-Holland Publishing Company, 1975.

Bottoms, Eric. "Navigation Needs." Seminars on River Basin Planning, Ft. Belvoir, Va. (27-31 May 1963: pp.291-310.

Braeutigam, Ronald R. and Roger G. Noll. "The Regulation of Surface Freight Transportation: The Welfare Effects Revisited." Review of Economics and Statistics. Vol. 66. (Feb. 1984): pp. 80-87.

Brown, Murray. "The Measurement of Capital Aggregates: A Postreswitching Problem." In The Measurement of Capital, edited by Dan Usher. Chicago: The University of Chicago Press, 1980.

Bundy, James M. and Dale W. Jorgenson. "Consistent and Efficient Estimation of Systems of Simultaneous Equations by Means of Instrumental Variables." in Frontiers in Econometrics edited by Paul Zarembka. New York: Academic Press.

Burt, Oscar R. and M. S. Stauber. "Economic Analysis of Irrigation in Subhumid Climate." American Journal of Agricultural Economics. Vol. 53, No. 1 (Feb. 1971): pp. 33-46.

Cady, Phillip D. and Richard Weyers. "Deterioration Rates of Concrete Bridge Decks." Journal of Transportation Engineering, ASCE. Vol.110. (January 1984): pp.34-44.

Champernowne, D. G. "The Production Function and the Theory of Capital: A Comment." Review of Economic Studies Vol.21 (1953-4): pp. 112-35

Cheney, Hollis B. "Engineering Production Functions." Quarterly Journal of Economics Vol. 53 No. 4. (November 1949): pp. 507-531.

--------. "Process and Production Functions from Engineering Data." In Studies in the Structure of the American Economy, edited by Leontief et al. New York: Oxford University Press, 1953.

Christensen, Laurits R., Dale W. Jorgenson and Lawrence J. Lau. "Transcendental Logarithmic Production Frontiers". (Feb [illegible]) pp. 28-45.

Churchman, C. West, Russell L. Ackoff and E. Leonard Arnoff. Introduction to Operations Research. New York: John Wiley & Sons, 1966.

Coen, R. M. 1974. "Revised Estimates of Service Lives and Capacity Depreciation Patterns of Manufacturing Equipment and Structures." Office of Tax Analysis. Department of Treasury.

Coen, Robert. "Investment Behavior, the Measurement of Depreciation and Tax Policy." American Economic Review 65. (March 1975): pp. 59-74.

--------. "Alternative Measures of Capital and Its Rate of Return in United States Manufacturing." In The Measurement of Capital. edited by Dan Usher. Chicago: The University of Chicago Press, 1980.

Comptroller General of the United States. General Accounting Office. Federal Capital Budgeting: A Collection of Haphazard Practices. PAD-81-19, February 26, 1981.

Dano, Sven. Nonlinear and Dynamic Programming. New York: Springer-Verlag, 1975.

Davis, John P. "Tonnage Capacity of Locks." Journal of the Waterways and Harbors Division ASCE (May 1969): pp. 201-213.

Denny, Michael. "Comment on Aggregation Problems in the Measurement of Capital." In The Measurement of Capital, edited by Dan Usher. Chicago: The University of Chicago Press, 1980.

DeSalvo, Joseph S. and Lester B. Lave. "An Analysis of Towboat Delays." Journal of Transport Economics & Policy (1969): pp. 232-241.

Diewart, W. E. "Aggregation Problems in the Measurement of Capital." In The Measurement of Capital, edited by Dan Usher. Chicago: The University of Chicago Press, 1980.

Dorfman, Robert. "An Economic Interpretation of Optimal Control Theory." American Economic Review. Vol. 59 (1969): pp.817-831.

Eckstein, Otto. Water Resources Development, the Economics of Project Evaluation. Cambridge: Harvard University Press, 1958.

Engineering News Record. "Construction Costs Tracked for U. S." (March 21, 1985): pp.98-105.

Federal Int-r-Agency River Basin Committee, Subcommittee on Benefits and Costs. "Proposed Practices for Economic Analysis of River Basin Projects". (May, 1950).

Fomby, Thomas B., et al. Advanced Econometric Methods. New York: Springer-Verlag, 1984.

Friedlander, Ann F. and Richard H. Spady. "A Derived Demand Function For Freight Transportation." Review of Economics and Statistics. Vol.62. (August 1980): pp. 432-441.

Friedman, Bernard and Mark Pauly. "Cost Functions for a Service Firm With Variable Quality and Stochastic Demand: The Case of Hospitals." Review of Economics and Statistics. Vol. 63. (November, 1981): pp. 620-624.

Gerber, Hans U. An Introduction to Mathematical Risk Theory. Wharton School, University of Pennsylvania, 1979.

Goldfeld, S. M. and R. E. Quandt. Nonlinear Methods in Econometrics. New York: North Holland Publishing Company, 1972.

Glaister, Stephen. Fundamentals of Transportation Economics. New York: St. Martin's Press. 1981.

Glassey, C. Roger and Sheldon M. Ross. "Queuing Models for Multiple Chamber Locks." September. Operations Research Center. Berkeley: University of California, (September, 1976).

Green, Donald W. "Capital Formation in the USSR, 1959-1974: An Econometric Investigation of Bureaucratic Intervention in the Process of Capital Construction." Review of Economics and Statistics. Vol. 60. (February, 1978): pp. 39-46.

Greene, William H. "On the Asymptotic Bias of the Ordinary Least Squares Estimator of the Tobit Model." Econometrica. Vol. 49, No. 2. (March, 1981): pp. 505-513

Greene, William H. "Estimation of Limited Dependent Variable Models by Ordinary Least Squares and the Method of Moments." Journal of Econometrics. 21. (1983): pp. 195-212.

Griliches, Zvi. Economies of Scale and the Form of the Production Function. New York: North Holland Publishing Company, 1971.

--------. "Specification Bias in Estimates of Production Functions." Journal of Farm Economics. Vol. 39 No. 1. (February, 1957): pp. 8-20.

--------. "Capital Stock in Investment Functions: Some Problems of Concept and Measurement." In Measurement in Economics, edited by Carl F. Christ et al. Stanford: Stanford University Press, 1963a, California.

--------. "Estimates of the Aggregate Agricultural Production Function from Cross-Sectional Data." Journal of Farm Economics 45. (1963b): pp. 419-428.

--------. 1964. "Research Expenditures, Education, and the Aggregate Agricultural Production Function."American Economic Review. Vol. 14 No. 6. December. pp. 961-974.

Haavelmo, Trygve. A Study in the Theory of Investment. Chicago: The University of Chicago Press, [illegible].

Halter, A. N., H. O. Carter and J. G. Hocking. "A Note on the Transcendental Production Function." Journal of Farm Economics, Vol. [illegible] ([illegible]), pp. [illegible].

Heady, Earl O. and John L. Dillon. Agricultural Production Functions. Ames: Iowa State University Press, 1961.

Helms, L. Jay. "The Effect of State and Local Taxes on Economic Growth: A Time Series Cross Section Approach." Review of Economics and Statistics, ([illegible]), pp. [illegible].

Hicks, John. Capital and Time. Oxford: Clarendon Press, 1973.

_____. "Capital Controversies: Ancient and Modern." American Economic Review Papers and Proceedings, (May, 1974).

Hillier, Frederick S. and Gerald J. Lieberman. Introduction to Operations Research. San Francisco: Holden Day, Inc., 1968.

Hirschman, Albert. The Strategy of Economic Development. New Haven: Yale University Press, [illegible].

Hirshleifer, Jack, James C. DeHaven and Jerome W. Milliman. Water Supply, Economics, Technology, and Policy. Chicago: The University of Chicago Press, 1960.

Holmes, Beatrice Hort. A History of Federal Water Resources Programs, 1800-1960. Department of Agriculture. Misc. Pub. No. 1233. Washington, D. C., 1972.

———. History of Federal Water Resources Programs and Policies, 1961-1970. Department of Agriculture. Misc. Pub. 1379. Washington, D. C., 1979.

Howe, Charles W. 1967. "Mathematical Model of Barge Tow Performance." Journal of the Waterways and Harbors Division ASCE. (November, 1967), pp. 153-166.

Howe, Charles, et al. Inland Waterway Transportation, Studies in Public and Private Management and Investment Decisions. Baltimore: Johns Hopkins Press, 1969.

Hulten, Charles R. and Frank C. Wykoff. "Economic Depreciation and the Taxation of Structures in United States Manufacturing Industries: An Empirical Analysis." In The Measurement of Capital edited by Dan Usher. Chicago: The University of Chicago Press, 1980.

Hulten, Charles R. and Frank Wykoff. "The Measurement of Economic Depreciation." In Depreciation, Inflation, and the Taxation of Income From Capital, edited by Charles Hulten. Washington, D. C.: The Urban Institute Press, 1981.

Hulten, Charles R. and George E. Peterson. "The Public Capital Stock: Needs, Trends, and Performance." American Economic Review. (May, 1984): pp. 166-173.

Intriligator, Michael D. Econometric Models, Techniques, & Applications. Englewood Cliffs: Prentice-Hall, Inc., 1978.

Intriligator, M. D. "The Application of Control Theory to Economics." in Lecture Notes in Control and Information Sciences, Analysis and Optimization of Systems. New York: Springer-Verlag, 1980: pp.607-627.

James, Douglas L. and Robert E. Lee. Economics of Water Resources Planning. New York: McGraw-Hill Company, 1971.

Jara-Diaz, Sergio R. " Transportation Product,Transportation Function and Cost Functions." Transportation Science (Nov., 1982): pp.522-539.

Jensen, Arne. Traffic, operational Research, Futurology. New York. North-Holland Publishing Co., 1980

Jerome, H. Mechanization in Industry. New York: National Bureau of Economic Research, 1934.

Johansen, L. Production Functions. New York: North Holland Publishing Company, 1972.

Johnson, J. Econometric Methods. New York: McGraw-Hill Book Co., 1972.

Judge, George G., et al. The Theory and Practice of Econometrics. New York: John Wiley and Sons, 1980.

Keeler, Theodore E. "Public Policy and Productivity in the Trucking Industry: Some Evidence on the Effects of Highway Investments, Deregulation, and the 55 MPH Speed Limit." American Economic Review, (May,1986): pp. 153-158.

Kelejian, Harry H. and Wallace E. Oates. Introduction to Econometrics. New York: Harper & Row, 1981.

Koutsoyiannis, A. Theory of Econometrics. Totowa: Barnes & Noble Books, 1985

Krutilla, John V. and Otto Eckstein. Multiple Purpose River Development. Studies in Applied Economic Analysis. Baltimore: The Johns Hopkins Press, 1958.

Larson, Robert E. and John L. Casti. Principles of Dynamic Programming, Part I. New York: Marcel Dekker, Inc., 1978.

Leigh, Wilhemina A. "Economic Depreciation of the Residential Housing Stock of the United States,1950-1970." Review of Economics and Statistics, Vol. 62, (May, 1980), pp. 200-207.

L'Esperance, W. L. "Interdependence vs. Recursiveness: A Review of the Debate and Notions of Causality in Economics." in Problems and Issues in Current Econometric Practice, edited by Karl Brunner. Columbus: Ohio State University, 1972.

Lientz, Bennet P. Computer Applications in Operations Analysis. New Jersey: Prentice-Hall Inc., 1975.

Louis Berger & Associates, Inc. "Performance Monitoring System Management Survey, Draft Report." East Orange, New Jersey, 1981.

Lowi, Theodore. "American Business, Public Policy, Case Studies and Political Theory." World Politics, vol. 16, (1964), pp. 677-715.

——— "Four Systems of Policy, Politics and Choice." Public Administration Review, No. 4, (July-August, 1972), pp. 298-310.

Maass, Arthur A. Muddy Waters. Cambridge: Harvard University Press, 1951.

Maddala, G. S. Econometrics. New York: McGraw-Hill Book Co., 1977.

------. Limited-dependent and Qualitative Variables in Econometrics. Cambridge: Cambridge University Press, 1983.

Mann, Nancy R., Ray E. Schafer, and Nozer D. Singpurwalla. Methods for Statistical Analysis of Reliability and Life Data. New York: John Wiley & Sons, 1974.

Martz, Harry F. and Ray A. Waller. Bayesian Reliability Analysis. New York: John Wiley & Sons, 1982.

May, Kenneth. "The Aggregation Problem for a One-Industry Model." Econometrica, Vol. 14 No. 3. (July, 1946): pp. 285-298.

McFadden, Daniel. "Conditional Logit Analysis of Qualitative Choice Behavior." in Frontiers in Econometrics, edited by Paul Zarembka. New York: Academic Press, 1974.

Mood, Alexander M., Franklin A. Graybill and Duane C. Boes. Introduction to the Theory of Statistics. New York: McGraw-Hill, 1974.

Morey, Edward R. "Confuser Surplus". American Economic Review (March, 1984) pp. 163-173

Morse, Phillip. Queues, Inventories, and Maintenance. New York: Wiley & Sons, 1958.

Murrell, Peter, Katherine Swartz and Bruce Vavrichek. "An Introduction to Qualitative and Limited Dependent Variable Models." Unpublished paper, Department of Economics, University of Maryland, (May, 1980)

National Waterways Foundation. U. S. Waterways Productivity, A Private and Public Partnership, Huntsville: The Strode Publishers, 1983.

National Waterways Study. U. S. Army Corps of Engineers Institute for Water Resources, Final Report Engineering Analysis of Waterways Systems. August, 1981.

--------. U. S. Army Corps of Engineers Institute for Water Resources, Final Report Evaluation of Alternative Future Strategies for Action, May, 1982.

--------. U. S. Army Corps of Engineers Institute for Water Resources, Final Report Evaluation of the Present Navigation System. March, 1982.

--------. U. S. Army Corps of Engineers Institute for Water Resources, Final Report Findings and Conclusions From Contractor Study Effort. May, 1982.

--------. U. S. Army Corps of Engineers Institute for Water Resources. National Waterways Study- A Framework for Decision Making- Final Report. January, 1983.

Norman, J. M. Heuristic Procedures in Dynamic Programming. Oxford: Manchester University Press, 1972.

Opaluch, James J. "A Heuristic Discussion of Optimal Control." University of Rhode Island. Department of Resource Economics Working Paper, undated.

Panico, Joseph A. Queuing Theory. Englewood Cliffs: Prentice Hall, Inc., 1959.

Petkau, A. John. 1978. "An Application of Dynamic Programming in Statistics." in Dynamic Programming and Its Applications, edited by Martin L. Putterman. New York: Academic Press, 1978: pp.221-232.

Pollak, Robert A., Robin C. Sickles and Terence E. Wales. "The CES-Translog Specification and Estimation of a New Cost Function". The Review of Economics and Statistics, (1984): pp.602-607.

Pope, Rulon and Jean-Paul Chavas. "Producer Surplus and Risk." Quarterly Journal of Economics Vol. C Supplement, (1985): pp. 853-864.

Reitman, Julian. 1971. Computer Simulation Applications. New York: John Wiley & Sons, 1971.

Renshaw, E.F. "Measurements of Benefits from Navigation Projects." American Economic Review. (September, 19__): pp.652-662.

Robinson, Joan. "The Production Function and the Theory of Capital." Review of Economic Studies Vol.21, (1953-4): pp.81-106.

Ruiz-Pala, Ernesto, Carlos Avila-Beloso and William W. Hines. Waiting Line Models. New York: Reinhold Press, 1973.

Samuelson, Paul A. 1962. "Parable and Realism in Capital Theory: The Surrogate Production Function." Review of Economic Studies Vol. 39, (1962): pp.193-206.

Sato, Kazuo. Production Functions and Aggregation. New York: North Holland Publishing Company, 1975.

Shultz, Richard P. "Graphic Analysis of Waterway Capacity." Journal of the Waterways and Harbors Division ASCE. (November, 196[illegible]) pp. 1[illegible]

Sloss, James. "Identifying and Predicting Profitability Components in the Bargeline and Railroad Industries." Transportation Research [illegible] (1968).

Small, Kenneth A. and Clifford Winston. "Efficient Pricing and [illegible] Solutions to Highway Infrastructure Needs." American [illegible] (May, 1986): pp. 165-169.

Solow, Robert. "The Production Function and the Theory of Capital." Review [illegible] Economic Studies. Vol. 23, (1955): pp. 101-108.

Solow, Robert. "Technical Change and the Aggregate Production Function." Review of Economics and Statistics. Vol. 39, (1957): pp. 312-

Swan, T. W. "Economic Growth and Capital Accumulation." Economic Record Vol. 32, (1956): pp.334-361.

Sweeney, Don, Michael Healy and Marilyn Fleming. "A Nonlinear Programming Model to Measure the Economic Impacts of Inland Navigation Problems." unpublished paper for The Institute for Water Resou[illegible] U. S. Army Corps of Engineers, (1985).

Taha, Hamdy A. Integer Programming Theory, Applications and Computatio[illegible] York: Academic Press, 1975.

Taubman, Paul and Robert Rasche. "Subsidies, Economic Lives and [illegible] Resource Misallocation." American Economic Review 61, [illegible] pp. 938-945.

Tobin, J. "Estimation of Relationships for Limited Dependent Variables." Econometrica. Vol. 26, No. 1, (Jan., 1958)

U. S. Army Corps of Engineers. Office of the Chief of Engineers. [illegible] Waterways Commodity Flows, Inland Navigation Systems Analysis [illegible]

--------. Institute for Water Resources. An Overview of the Potential Role of the Inland Waterways in an Integrated U. S. Transportation System, Contract Report 75-5, (August, 1975).

--------. INSA Commodity Flow Analysis. Inland Navigation Systems Analysis Vol. 3, (1976).

--------. INSA Multimodal Analysis. Inland Navigation Systems Analysis Vol. 4, (1976).

--------. INSA Waterway Analysis. Inland Navigation Systems Analysis Vol. 5, (1976).

--------. Office of the Chief of Engineers. Physical Characteristics of Inland Waterways; Table A; Locks, EP 1105-2-11, April 1, 1976.

--------. Institute for Water Resources. Comprehensive Master Plan for the Management of the Upper Mississippi River System. Technical Report A: Navigation and Transportation, 1981.

--------. Digest of Water Resources Policies and Authorities, Ep 1165-2-1, 1981.

--------. Institute for Water Resources. Overview of the Transportation Industry, August, 1981.

--------. Engineer Institute for Water Resources. A Statistical Survey of Vessel Performance and Configuration Characteristics on Inland Waterways, Research Report 83R-1, February, 1983.

--------. Rock Island District. Mississippi River Clinton, Iowa Lock and Dam 13 Reconnaissance Report Major Rehabilitation, December, 1984.

--------. Engineer Institute for Water Resources. Overview of the Lock Performance Monitoring System, Pamphlet 84-PM-1. October, 1984.

--------. Engineer Institute for Water Resources. The 1982 Estimated Value of Waterborne Commodities, Research Report 84-R-2. February, 1984.

--------. Waterway Experiment Station. The Condition of Corps of Engineers Civil Works Concrete Structures, Technical Report REMR-CS-2, April, 1985.

--------. Engineer Institute for Water Resources. Literature Survey of Induced Traffic Due to Transport Cost Savings, Working Paper 85-WP-1, June, 1985.

--------. Project Operation The Performance Monitoring System (RCS DAEN-CWZ-5), Engineering Pamphlet 1130-2-418. 29 June, 1985.

--------. Engineer Institute for Water Resources. Performance Monitoring System: Summary Statistics For date. Quarterly Summary Report year-SR-1.

--------. Office of the Chief of Engineers. Waterborne Commerce of the United States, Calendar Year date, annual.

--------. Project Operation Major Rehabilitation Program, Engineering Regulation 1130-2-417.

U. S. Congress, House, Subcommittee on Evaluation Standards. Proposed Practices for Economic Analysis of River Basin Projects, May, 1958.

--------. Senate. Policies, Standards, and Procedures in the Formulation, Evaluation, and Review of Plans for Use and Development of Water and Related Land Resources. S. Doc. 97, 87th Congress, 2nd Session, 1962.

U.S. Department of Commerce. A Study of Public Works Investment in the United States, by CONSAD Research Corporation, April, 1980.

--------. A Study of Public Works Investment in the United States-Appendices, by CONSAD Research Corporation, April, 1980.

U. S. Department of the Interior. Bureau of Reclamation. Construction Cost Trends, October, 1985.

van der Ploeg, Frederick. Mathematical Methods in Economics. New York: John Wiley & Sons, 1984.

Walters, A. A. "Production and Cost Functions. An Econometric Survey." Econometrica, Vol. 31 No. 1, (Jan.,1963): pp. 1-66.

Yoe, Charles. The Declining Role of the U. S. Army Corps of Engineers in the Development of the Nation's Water Resources. Fort Collins: Colorado Water Resources Research Institute, 1981.

Young, Allan H. and John C. Musgrave. "Estimation of Capital Stock in the United States." In The Measurement of Capital, edited by Dan Usher. Chicago: The University of Chicago Press, 1980.

Young, Robert A. and S. Lee Gray. Economic Value of Water: Concepts and Empirical Estimates. Ft. Collins: Colorado State University, 1973.

Zellner, A. and N. S. Revankar. "Generalized Production Functions." Review of Economic Studies, (1969): pp. 241-248.

END

10-87

DTIC