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TECHNOLOGY AND PRODUCTIVITY IN HIGHWAY CONSTRUCTION

by

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PREFACE

This report is one of a series of publications which describe various studies undertaken under the sponsorship of the Technology Adaptation Program at the Massachusetts Institute of Technology.

In 1971 the United States Department of State, through the Agency for International Development, awarded the Massachusetts Institute of Technology a grant, the purpose of which was to provide support for the development at M.I.T., in conjunction with institutions in selected developing countries, of capabilities useful in the adaptation of technologies and problem-solving techniques to the needs of those countries. At M.I.T., the Technology Adaptation Program provides the means by which the long-term objective for which the A.I.D. grant was made, can be achieved.

This report investigates the role of technology in the construction industry, and its influence on productivity and efficiency and product quality and cost. For the U.S. and other developed countries, this is of importance in terms of indicating the direction in which technology has advanced in the past and might do so or be encouraged to do so in the future. As for the developing countries, it is of importance in terms of assessing the potential appropriateness of various technologies in light of their local technical, economic, and social conditions.

This analysis of technology and its progression over time concentrates on the identification and quantification of the magnitude and nature of the technology change that has occurred. Of particular interest is whether the observed technology change has been characterized by increasing efficiency or by factor substitution (equipment for labor) or, more likely, a little of both, in which case the extent of their contributions is of interest. Finding technology change to have been primarily in the direction of substitution, for example, indicates, for the U.S. and other developed countries, the necessity of redirecting efforts in the future toward developing new technical alternatives more able to cope with the upcoming shortages in the materials and energy areas and perhaps also to increase efficiency rather than just substitute. The implication of change characterized by increased efficiency, on the other hand, is that there really has been technological advance, and there is no reason to try to alter its course in the future, as long as the means by which it has been achieved remain viable. For the developing countries, technology change in the direction of increased efficiency suggests that technology may not be too reversible, and that new alternatives in the software and/or hardware areas may need to be developed. The implication of change characterized by substitution, however, is that technology may potentially be reversible, and that it may be worthwhile

to begin to more seriously consider and evaluate some of the older, more labor and animal-intensive techniques for use in the developing countries.

The highway sector of the construction industry in the U.S. provides a good basis for this research. The technology of this sector in the U.S. has undergone considerable change over the past fifty years or so. Furthermore, it has certain advantages over other sectors of the construction industry in terms of such a study, including the limited number of steps which constitute the construction process, the measurability of its output, and the availability of the necessary data.

In the process of making this TAP-supported study, some insight has been gained into how appropriate technologies can be identified and adapted to the needs of developing countries per se, and it is expected that the recommendations developed will serve as a guide to other developing countries for the solution of similar problems which may be encountered there.

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LIST OF ABBREVIATIONS

site prep	= site preparation
exc/haul	= excavation/hauling
spr/comp	= spreading/compaction
grvl	= gravel
wbm	= waterbound macadam
dbst	= double bituminous surface treatment
dbst/g	= double bituminous surface treatment on a gravel base
dbst/w	= double bituminous surface treatment on a waterbound macadam base on a gravel subbase
tp	= technical package
p	= project
mm	= millimeter
cm	= centimeter
M	= meter
km	= kilometer
in.	= inch
ft,'	= foot
yd	= yard
mi	= mile
SM	= square meter
ha	= hectare
sf, ft^2	= square foot
sy	= square yard
CM	= cubic meter
LCM	= loose cubic meter
BCM	= bank cubic meter
CCM	= compacted cubic meter
ft^3	= cubic foot
cy	= cubic yard
lcy	= loose cubic yard
bcy	= bank cubic yard
ccy	= compacted cubic yard
fpm	= feet per minute
mph	= miles per hour
hp	= horsepower
dbhp	= drawbar horsepower
fwhp	= flywheel horsepower
ct	= count
qty	= quantity
sngl	= single
dbl	= double
max	= maximum
int/dep	= interest and depreciation
maint/misc	= maintenance and miscellaneous items
ADT	= average daily traffic

HCM = Highway Cost Model - citation:
Moavenzadeh, Fred, Fredric Berger, Brian Brademeyer, and Robert Wyatt, The Highway Cost Model - General Framework, Report No. 75-4, Technology Adaptation Program, Massachusetts Institute of Technology, Cambridge, September 1975.

SUMMARY

The construction industry holds a prominent position in the U.S. economy, not only in terms of its direct contributions to the gross national product and to employment, but also through its provision of physical facilities satisfying a wide variety of social, economic, and technical needs. In light of this, the tendency of construction, over the past fifteen years or so, to consistently exhibit higher price escalation than is the case in industry in general, has generated widespread concern among industry and government officials alike. Rising factor prices without commensurate increases in factor productivities is a frequently cited contributory condition. Productivity is a complex issue in construction where even labor productivity, let alone capital, materials, or total factor productivity, is extremely difficult to measure, due to the heterogeneity of the industry's products as well as of its inputs. Although progress is being made, particularly in the development of measures of labor and materials productivity in individual sectors of construction, measures of capital and total factor productivity are still lacking, and the process of determining the factors influencing this productivity still remains a speculative one.

The role of technology in the construction industry and its influence on productivity and efficiency and product quality and

cost is the general focus of the current research. For the U.S. and other developed countries, this is of importance in terms of indicating the direction in which technology has advanced in the past and might do so or be encouraged to do so in the future; as for the developing countries, it is of importance in terms of assessing the potential appropriateness of various technologies in light of their local conditions. In this analysis of technology and its progression over time, efforts are concentrated on the identification and quantification of the magnitude and nature of the technology change that has occurred. The issue of particular interest is whether the observed technology change has been characterized by increasing efficiency or by factor substitution (equipment for labor) or, more likely, a little of both, in which case the extent of their contributions is of interest. The highway sector of the construction industry in the U.S. provides a good basis for this study.

A micro-study approach is pursued in this investigation of technology and productivity in highway construction in the U.S. The basic analytic procedure thus entails first observing and recording the inputs required for and influences impacting the various tasks of production, for alternative means of producing a given output, and then using this data to synthesize a production isoquant for the good which is subjected to further economic analysis.

Since it is obviously impossible to actually observe the technologies of the past in the field today, historical data used in a simulation framework must suffice, whereby the various stages of highway construction and complete road projects can be hypothetically built and operated, by means of alternative technical packages and project designs. This is accomplished in two levels of analysis: (1) the stage-level, wherein each stage is considered separately in the analysis of technology and its change; and (2) the project-level, wherein the stages are brought together to form various projects such that the interaction of design and technology in highway construction and operation might be taken into account.

The role of technology in the productivity of highway construction over the years in the U.S. appears indeed to have been a significant one. Highways can be constructed today using considerably less labor and even less capital than was possible in the second and third decades of this century. These advances in highway construction technology appear to have played a major part in keeping project costs down over the years.

Efficiency seems to have played a major role in the observed technology change, although the magnitude and rate of the decrease in resource requirements attributable to efficiency has lessened over time. Substitution brought about by factor price changes, on the other hand, seems to have had effectively no part in the technology change, although it seems likely that expectations of

labor's cost rising relative to that of capital, among other conditicns, may have tended to induce technology change in the direction of saving labor as was observed.

Increased mechanization and the introduction of new types of equipment appear to constitute the primary means of accomplishment of such technology change before the fifties, while since then it has been largely just improving the equipment and the effectiveness with which it is used. As for the future, although the same basic motivations may be expected to continue, perhaps in a somewhat dampened state, gains in productivity and efficiency achieved by a simple continuation of past means of accomplishing change may be expected to be somewhat less than those previously, if past trends can be taken as indicative of those of the future. As for the developing countries, it appears that the development of technical packages since the early part of this century has been focused on the capital-intensive end of the production isoquant; the labor and animal-intensive packages of the past seem to have been essentially forgotten, although they still appear to be efficient and, under some conditions, economic and their use potentially worth considering.

CHAPTER 1

INTRODUCTION

1.1 Productivity in Construction in the United States

The construction industry's role in the overall functioning of the U.S. economy is one of considerable importance. In recent years, the value of new construction put in place has accounted for some 9 to 11 percent of the gross national product, while the industry has provided some 4 to 6 percent of the nation's nonagricultural employment. Highway construction's share is some 7 to 11 percent of the output and 8 to 10 percent of the employment generated by the industry. At the same time, variations in the rate and level of investment in the industry's various activities have served as a stabilizing influence on the overall economy. Finally, through the provision of physical facilities, the construction industry plays a major role in satisfying society's needs for shelter, infrastructural services, and institutional, commercial, and manufacturing services; in fact, the overall ability of other industries to produce and distribute goods and services for consumers is heavily dependent upon the construction industry.

In light of the industry's prominent position, its tendency, over the past fifteen years or so, to consistently exhibit higher price escalation than is the case in industry in general, has generated widespread concern among industry and government officials alike. The price trends* exhibited

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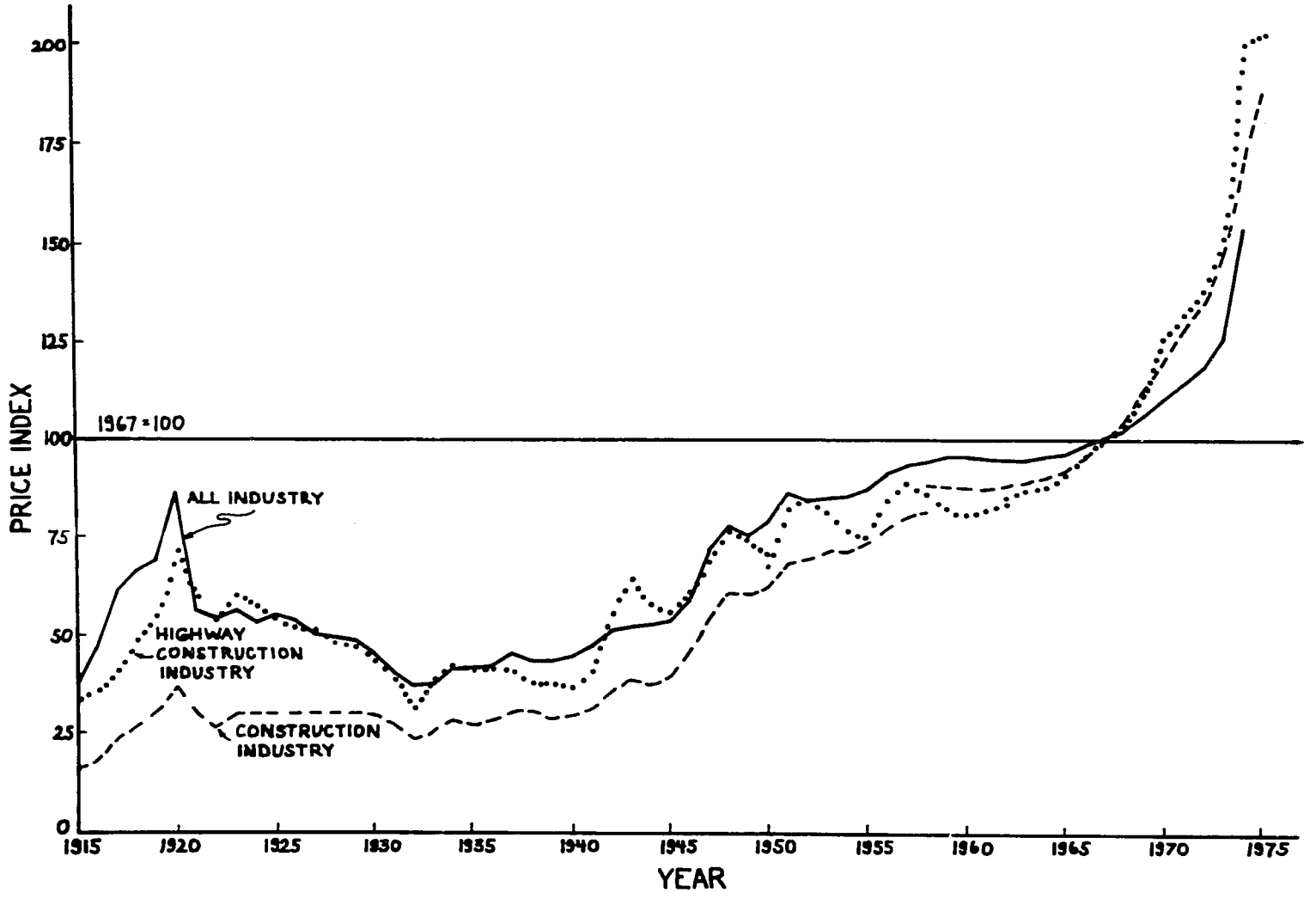
* The term price trend is used somewhat loosely here in the case of the construction industry, in that the index is actually based on the costs of the inputs rather than the price of the output and may, therefore, have a certain upward bias (71).

by industry in general and the construction and highway construction sectors over the last sixty years are given in Figure 1.1. As for general trends exhibited by the three categories of industry, up to about World War II the peaks and valleys in the prices essentially balance out, yielding only a slightly upward trend; at that time a distinctly upward trend begins, which continues at a moderate rate to the mid-sixties, when the prices begin a rapid ascent. In the particular case of highway construction's price, it is of interest to note that it generally moves in line with all industry's until the post-war period, at which time it fluctuates around a bit until 1960, when it begins its rapid ascent, similar to that of construction and even exceeding it.

A condition commonly cited as contributing to such price escalation is rising factor prices without commensurate increases in factor productivities. As labor generally constitutes a sizeable share of the costs and is more readily measurable than is capital or materials, output per man-hour is commonly used as a measure of productivity; Figure 1.2 gives the trends in labor productivity exhibited by the three industry categories over the past thirty years or so. For construction in general and highway construction in particular, labor productivity on the average rises steeply until the late fifties or early sixties, at which point it fluctuates for construction, with the peaks and valleys essentially balancing out to no further growth, while it continues a steady upward trend at a somewhat reduced pace for highway construction; it should be noted that this is the same point at which prices began to rapidly escalate in both sectors. As for all industry, its labor productivity exhibits exactly opposite trends; it might be remembered that its recent price escalation has not been quite as rapid as that of the

Figure 1.1: Price trends exhibited by industry in general and the construction and highway construction sectors over the past sixty years (source: ref. 19, 86, 91, 104).



(Figure 1.1 continued)

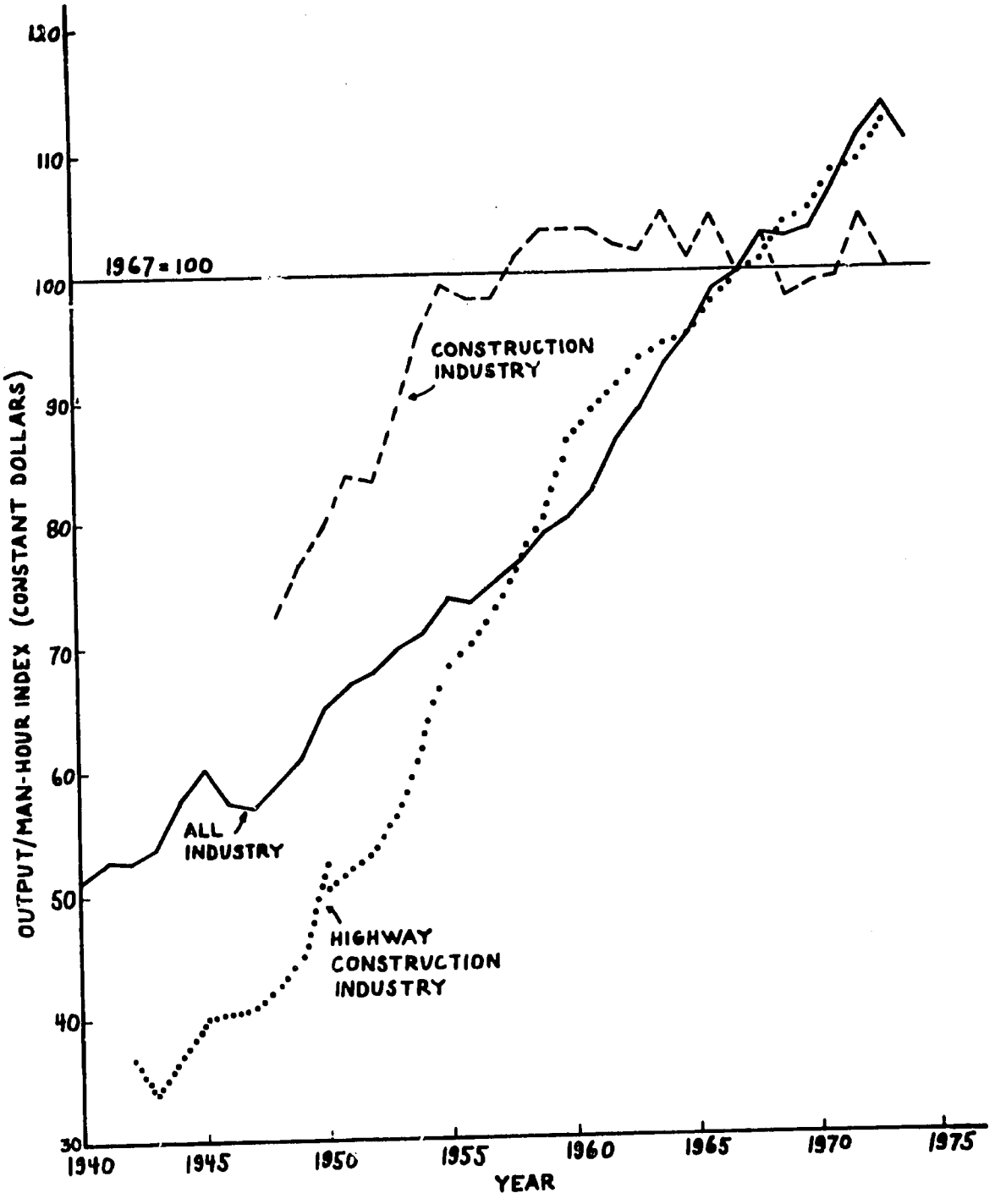
Note:

•••••Highway construction industry index is the U.S. Federal Highway Administration's composite contract bid price index for 1922-75, the breaks in the curve representing points in time when the quantities of common excavation, surfacing, and structures used in the derivation of the composite index have been changed; the U.S. Department of Commerce extrapolated the data back to 1915 by means of weighted averaging of various relevant indexes (19, 86, 104).

----Construction industry index is the U.S. Department of Commerce's composite cost index, which is a combination of various indexes weighted by the relative importance of the major classes of construction; as the index is ultimately based on costs of inputs rather than the price of output, it is more properly termed a cost, rather than price, index. The U.S. Department of Commerce revised the index at the time the base was changed to 1967, but did so only back to 1958 (19, 86).

——All industry index is the U.S. Bureau of Labor Statistics wholesale price index for industrial commodities (91).

Figure 1.2: Trends in output per man-hour exhibited by industry in general and the construction and highway construction sectors over the past thirty years or so (source: ref. 86, 87, 89, 91, 101, 103).



(Figure 1.2 continued)

Note:

····· Highway construction industry index is based on the U.S. Federal Highway Administration's figures on man-hours per thousand dollars of construction, adjusted to 1954 constant dollars, for 1950-73; prior to 1950, it is based on their figures for man-hours used per thousand dollars of construction, award or job-started basis, in current dollars, inflated to 1954 constant dollars using their composite bid price index. This output per man-hour index thus covers only on-site employees (86, 101, 103).

---- Construction industry index is the U.S. Bureau of Labor Statistics' output per man-hour index for all persons in the construction industry (89).

—— All industry index is the U.S. Bureau of Labor Statistics' output per man-hour index for all persons in the nonfarm sector of the economy, based on establishment data (87, 91).

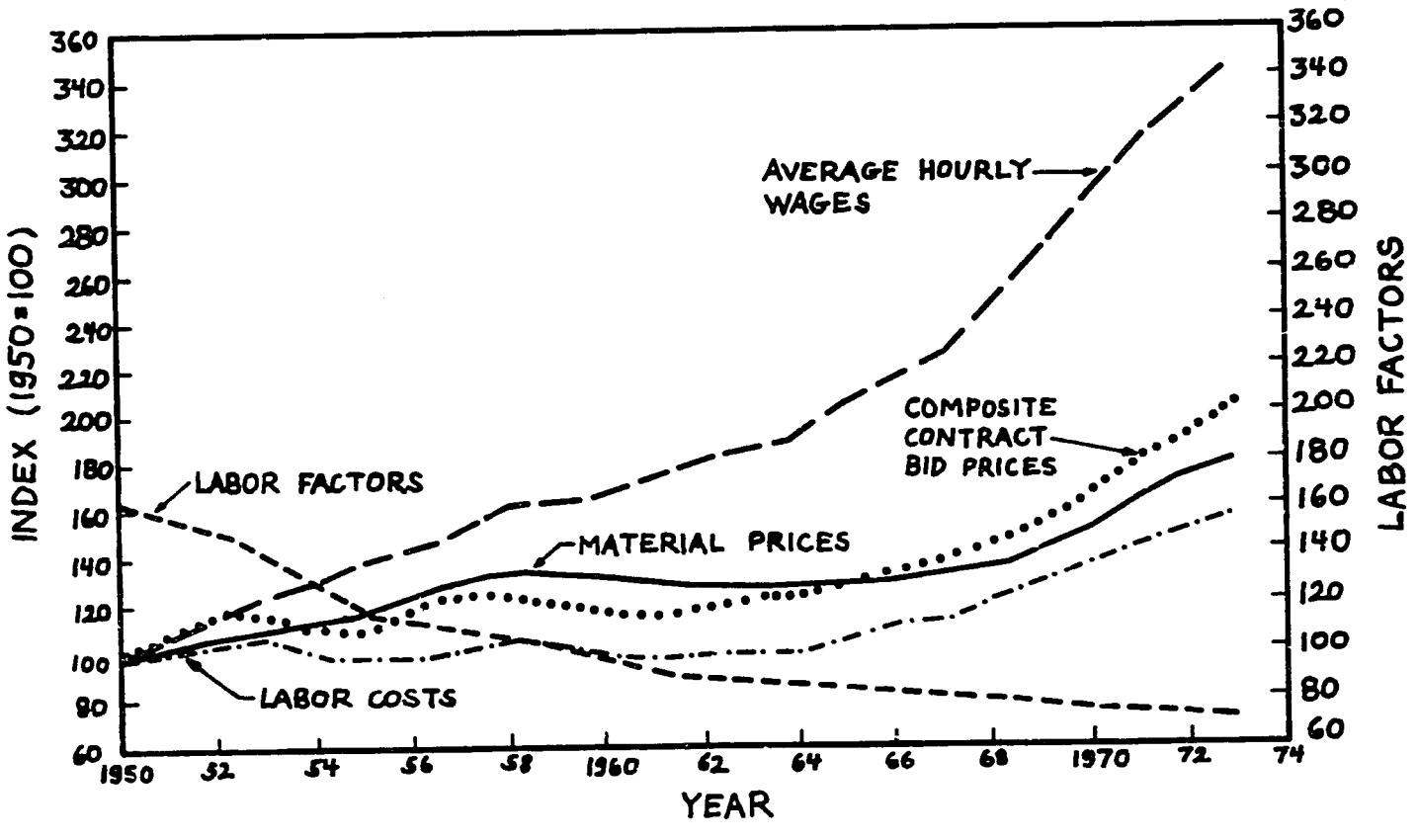
construction sectors. Figure 1.2 also shows that prior to the sixties, highway construction exhibits the highest average rate of productivity growth, with general construction coming in second; after the early sixties turning point, highway construction's rate of growth drops to below that of all industry, while general construction's essentially goes to zero.

The implication of this is that productivity growth prior to the sixties in construction in general and highway construction in particular is reasonably successful at offsetting factor price increases, but since then its reduced rate of growth in conjunction with the increased rate of inflation in factor prices results in productivity's being less successful at offsetting price changes. Figure 1.3 suggests that this is indeed the case for highway construction, showing labor costs (i.e., the product of average hourly wages and manhours required per 1,000 constant dollars of construction) as reasonably constant from 1950 to 1964, at which time they begin to rise.

It might also be noted that although composite contract bid prices follow labor costs reasonably closely in Figure 1.3, it is, not surprisingly, not an exact match, especially in recent years. There are other factors of production, namely materials and capital, the prices and productivities of which have also changed over time, as well as other conditions, such as the magnitude and nature of demand for the product, which influence the final price. Table 1.1 shows the percentage distribution of construction costs among the various factors of production for different types of construction, demonstrating the significance of these other input factors in overall project costs.

Setting aside for the moment concerns over the incompleteness of labor productivity and price as an indicator of productivity and price trends in

Figure 1.3: Cost and labor usage trends for highway construction since 1950 (source: ref.101).



(Figure 1.3 continued)

Note:

•••• Composite contract bid price index, converted from award to expenditure basis.

— — Average hourly wage index.

---- Labor factors, man-hours used per thousand dollars worth of construction, adjusted to 1954 constant dollars.

-·-· Labor cost index, based on product of average hourly wages and labor factors.

—— Material price index, based on weighted average of unit prices for Portland cement, asphalt, aggregates, steel, and lumber.

Table 1.1: Percentage distribution of construction costs, by type of construction, in the U.S. (source: ref. 28, 93, 108).

Type of Construction and Year	On-Site Wages	Materials	Equipment	Overhead and Profit[a]
Federally-aided highways				
1973	24.6	44.5	-[b]	30.9[b]
1970	25.6	45.0	-[b]	29.4[b]
1967	24.8	47.8	-[b]	27.4[b]
1964	26.0	50.3	11.1	12.6
1961	24.7	52.6	11.7	11.0
1958	23.9	50.6	12.0	13.5
Elementary & secondary schools				
1964-65	25.8	54.2	1.0	19.0
1959	26.7	54.1	1.4	17.8
Hospitals				
1965-66	29.6	50.4	1.3	18.7
1959-60	28.2	53.2	1.2	17.4
Public housing				
1968	32.4	41.9	1.5	24.2
1959-60	35.5	45.0	2.5	17.0
Private single-family housing[c]				
1969	20.4	43.4	0.9	35.3
1962	22.1	47.2	1.0	29.7
Sewer works				
lines 1962-63	24.3	44.5	11.2	20.0
plants 1962-63	26.6	49.2	8.2	16.0
Civil works (Corps. of Eng.)				
land operations 1959-60	26.0	35.0	19.3	19.7
dredging 1959-60	32.3	17.3	24.9	25.5
Federal office buildings				
1959	29.0	51.4	1.9	17.7
College housing				
1960-61	29.3	52.6	1.6	16.5
Multi-family housing				
1971	27.9	44.2	3.0	24.8

(Table 1.1 continued)

[a]Includes off-site wages, fringes, construction financing costs, inventory, and other overhead and administrative expenses as well as profits.

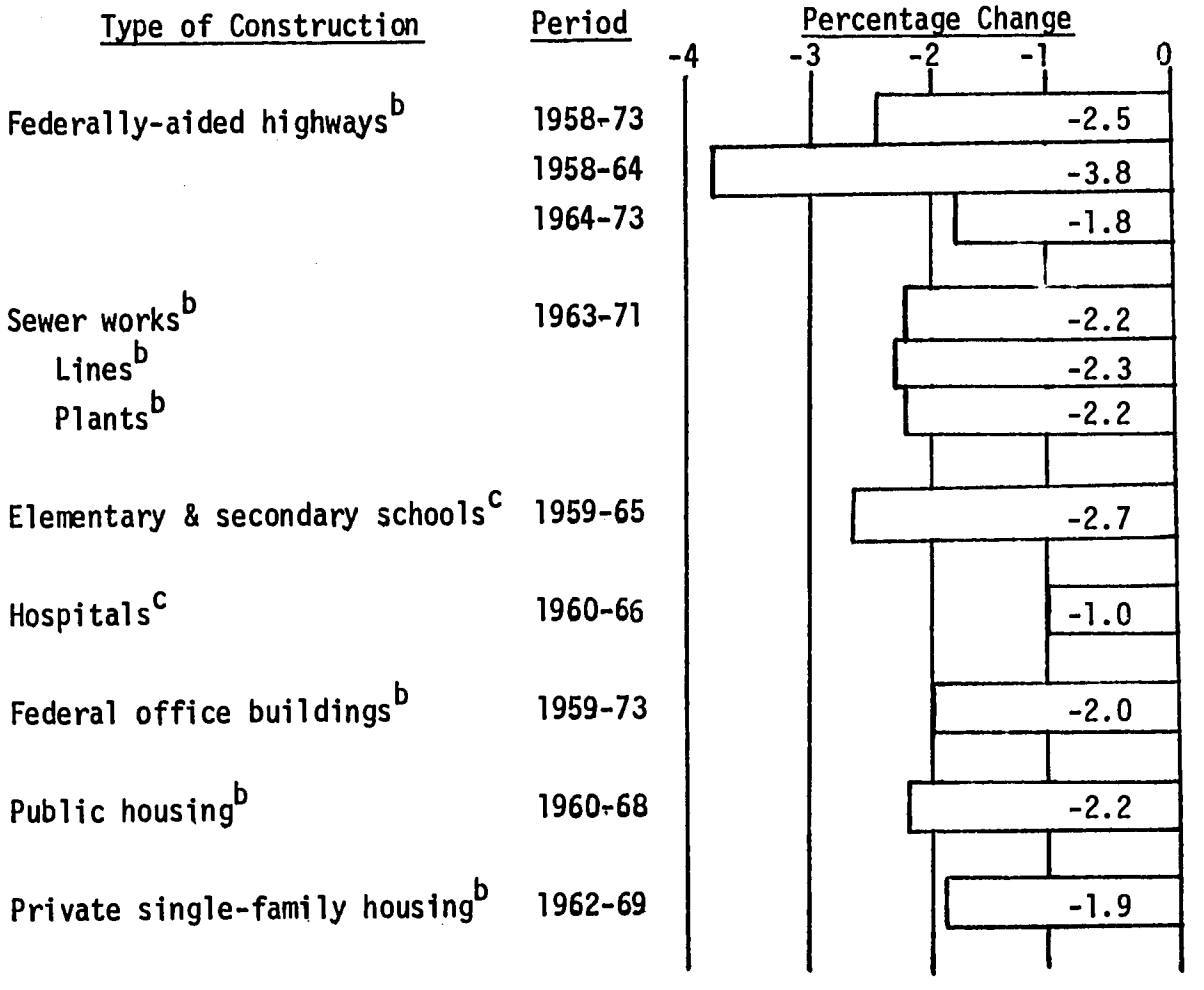
[b]Equipment included in overhead and profit.

[c]Construction costs include selling expenses in addition to construction contract costs (selling expenses were 2.9 percent in 1969).

construction, considerable disagreement still remains as to the appropriate means by which to measure labor productivity in the construction industry. The results of six different methods of estimating output per man-hour indexes for contract construction, for example, are five different figures, ranging from 1.6 to 3.0 percent, for the average annual rate of growth over about a twenty-year period beginning around 1947 (16, 22, 30, 89). The primary difficulty is the heterogeneous nature of the industry's output, ranging from single-family homes to skyscrapers, industrial plants, and highways, each of which is distinct in its own right in terms of its function, size, quality, performance characteristics, and so forth, while each also has rather different requirements in terms of the type and quantity of labor, let alone the other factors of production; moreover, the nature and mix of products in a single sector of construction is continuously changing, let alone that in the industry as a whole. Such features make the derivation of a reliable output measure, such as the deflated price of a reasonably constant product set, very difficult and also make the meaning and usefulness of a measure of the industry's labor productivity somewhat questionable. Another area of difficulty lies in the measurement of the inputs, in that labor is not homogeneous either, although it is generally assumed to be thus.

As a result of these difficulties, certain agencies have begun working with the individual sectors of construction; the U.S. Bureau of the Census, for example, has begun developing price indexes for each sector, while the U.S. Bureau of Labor Statistics since the late fifties has been studying the labor and materials requirements of the various sectors. Figure 1.4 gives some of the results of these efforts, in the form of a chart of average annual percentage changes during the sixties in on-site man-hours

Figure 1.4: Average annual percentage change in on-site labor requirements, by type of construction, for selected periods 1958-1973 (source: ref. 28, 88).



[a]Compound interest method.

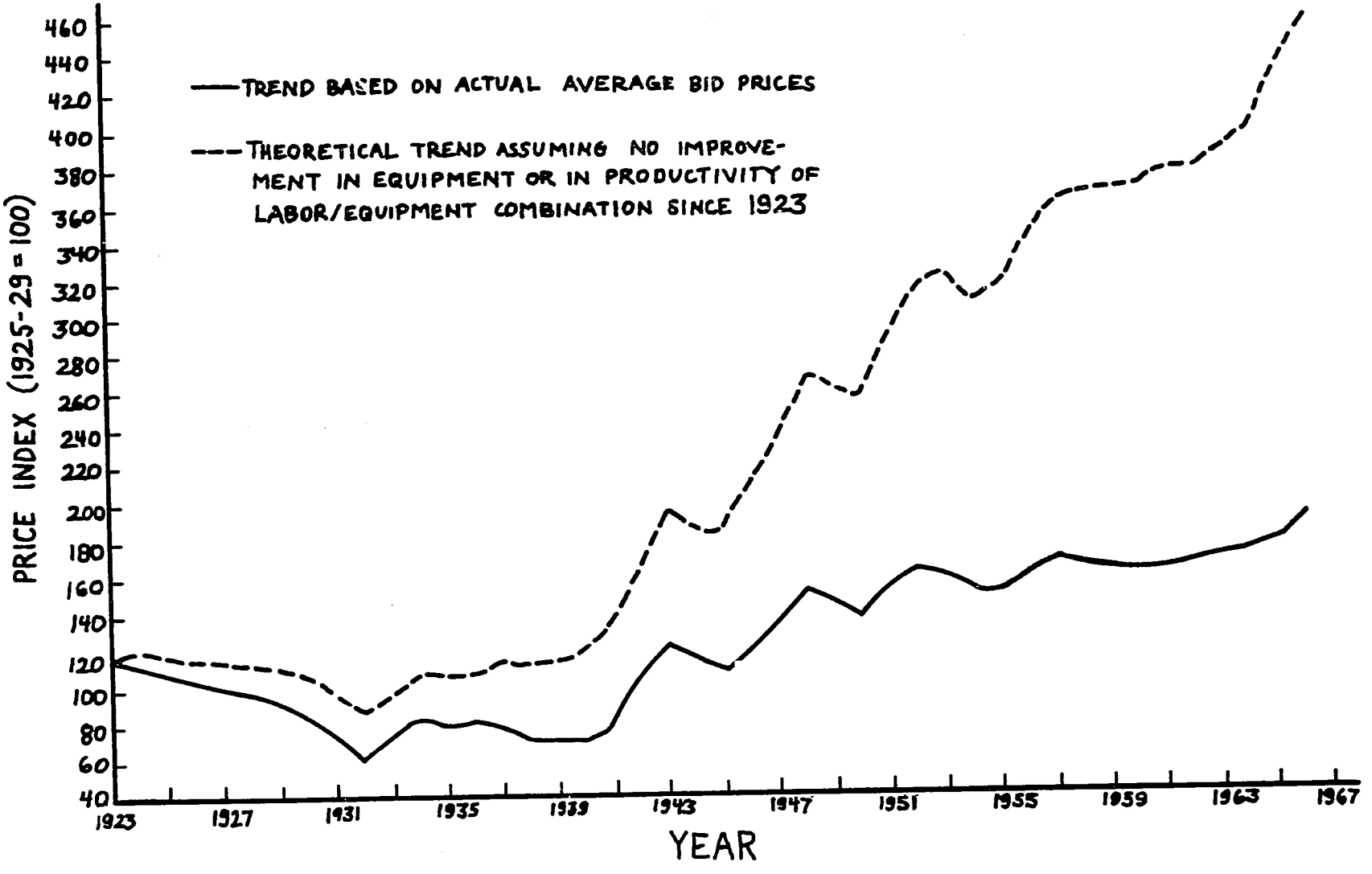
[b]Deflated dollars output measure.

[c]Square feet output measure.

required per unit of output for various types of construction. In line with Figure 1.2, Figure 1.4 suggests that the growth of highway construction's labor productivity has slowed significantly in recent years, although over the full analysis period it still appears to be higher than that of the other sectors of construction, excepting schools. The results for the industry as a whole, however, look much more favorable in terms of the construction industry's exhibiting productivity growth during the sixties, than do those of Figure 1.2. The validity of these new measures will be considerably strengthened by frequent follow-up studies, as have been done for highways at three-year intervals, and by further work in the area of deriving price indexes and other means to achieving reliable measures of output.

Although these new measures of productivity appear promising, measures of capital and total factor productivity are still lacking, and the process of determining the factors influencing this productivity still remains a speculative one. Of primary interest in the current research, for example, is an investigation of the role of technology in the productivity of highway construction in the U.S. Figure 1.5, which shows the trend over time of highway construction bid prices, both as it actually occurred and as it would have occurred had technology not changed as it did, suggests that technology did, indeed, have a significant influence on project costs and presumably factor productivities. Knowing this and knowing that the industry's man-hours requirements dropped over time give little insight into the nature of this technology change however. Labor productivity over time might, for example, have appeared to improve as a result of substituting the cheaper resource, capital, for the more expensive one, labor, as factor

Figure 1.5: Bid price trend for highway construction, both as it actually occurred and as it would have occurred had technology remained constant at that of 1923 (source: ref.100).



prices changed, resulting in a lowering of capital productivity; or labor's productive efficiency might actually have improved, perhaps as a result of implementing technological innovations, such that requirements for both labor and capital were reduced; or both events might have occurred. It is issues of this sort that the current research tries to address. Such knowledge and understanding of the nature of technology change of the past is of utmost importance to industry and government alike if they are to take an active part in guiding technology's course in the future.

1.2 The Situation in Developing Countries

The levels of open unemployment and underemployment and more particularly the growing gap between the rate of new entries to the labor force and the capacity of the economy to absorb them, even in countries where the growth of output is reasonably high, is a problem of increasing concern to many planners in developing countries. Closely akin to this problem is that of inequitable income distribution and poverty in the developing world. At the same time, their supply of capital, by and large, is very limited, forcing them to rely heavily on external loans and grants-in-aid for capital formation. With conditions as they now stand in developing countries, the labor surplus which currently exists, and is expected to grow, cannot be fully utilized without an increase in the supply of capital. A perhaps more feasible solution is to substitute the abundant labor for the scarce capital, thereby generating more employment and output than would be possible otherwise. The developed and developing countries and international agencies in their search for sectors of the economy where substitution might be possible have focused considerable attention on construction, particularly the public works area and even more specifically highways.

Public works facilities play an early and major role in economic development, and represent a large and visible portion of government investment. This makes them a rather natural target for labor-capital substitution. Moreover, being in the public domain, the work can more readily be monitored by the government which can thus enforce the use of labor-intensive techniques and perhaps adjust project timing, for example, to coincide with seasonal surpluses. Finally, the potential for employment in this sector appears promising, especially for the unskilled which is where the surplus lies and the rural underemployed, in that such activities were executed by labor using simple tools and animal power in the past.

Regardless of the labor abundance and capital scarcity in the developing world, the more mechanized techniques developed in the labor-scarce, capital-abundant countries of the developed world have been transferred to and adopted by the developing countries for use in public works and particularly highway construction. Two possible explanations may account for this apparent contradiction: (1) the set of efficient technical alternatives is not, or at least appears not to be, fully defined over the range of possible labor/capital mixes; and (2) inappropriate factor prices (i.e., market prices rather than prices reflecting the relative scarcity and thus the social cost of the various resources) are used in the selection of the labor/capital mix. It is the first alternative which can conveniently be investigated to a limited extent in the course of the current research. If technology change over time in the U.S. is found to be primarily in the direction of increasing efficiency, for example, the more capital-intensive packages of today may comprise the only set of efficient alternatives currently available, although new developments in the direction of utilizing

labor may still be possible. Alternatively, it may be that some of the more labor-intensive packages of the past are equally efficient (e.g., technology change may have been largely in the direction of simple substitution of equipment for labor), but that they have been forgotten in the labor-scarce developed countries, or that institutional biases and rigidities in the developing countries themselves prevent their use. Such insights into the progression of technology over time in the U.S. are thus potentially of value to those concerned with the issue of labor-capital substitution, particularly in terms of ascertaining the feasibility of certain developing countries' returning to the use of some of the more labor and animal-intensive techniques of the past.

1.3 Purpose and Scope of Research

The general focus of the research is the role of technology in the construction industry, and its influence on productivity and efficiency and product quality and cost. For the U.S. and other developed countries, this is of importance in terms of indicating the direction in which technology has advanced in the past and might do so or be encouraged to do so in the future; as for the developing countries, it is of importance in terms of assessing the potential appropriateness of various technologies in light of their local technical, economic, and social conditions.

In this analysis of technology and its progression over time, efforts are concentrated on the identification and quantification of the magnitude and nature of the technology change that has occurred. The issue of particular interest is whether the observed technology change has been characterized by increasing efficiency or by factor substitution (equipment

for labor) or, more likely, a little of both, in which case the extent of their contributions is of interest. Finding technology change to have been primarily in the direction of substitution, for example, indicates, for the U.S. and other developed countries, the necessity of redirecting efforts in the future toward developing new technical alternatives more able to cope with the upcoming shortages in the materials and energy areas and perhaps also to increase efficiency rather than just substitute. The implication of change characterized by increased efficiency, on the other hand, is that there really has been technological advance, and there is no reason to try to alter its course in the future, as long as the means by which it has been achieved remain viable. For the developing countries, technology change in the direction of increased efficiency suggests that technology may not be too reversible, and that new alternatives in the software and/or hardware areas may need to be developed. The implication of change characterized by substitution, however, is that technology may potentially be reversible, and that it may be worthwhile to begin to more seriously consider and evaluate some of the older, more labor-intensive techniques for use in the developing countries.

The highway sector of the construction industry in the U.S. provides a good basis for this research. Narrowing the scope to a single sector of the construction industry follows directly from the discussion above of the heterogeneity of the industry's products; limiting it to a single country seems only appropriate in view of the wide variation in both inputs and outputs in this single sector from one country to another, making comparisons, for example, of technical alternatives and associated productivities difficult. The highway sector is a particularly

interesting sector of the construction industry to study in the U.S., in that its technology has undergone considerable change over the past fifty years or so. Furthermore, it has certain advantages over other sectors of the construction industry in terms of such a study, including: (1) only a few basic steps constitute the construction process, thereby lessening the number of possible interactions and making more possible the study of both the individual steps and the overall project; and (2) its output is more readily measurable in quantity, quality, and use terms. Finally, data also appear to be reasonably available for the highway sector, stemming largely from the U.S. Federal Highway Administration's production studies of alternative highway construction methods carried out in the 1920's, 1950's, and 1970's. In summary then, the focus of the current research is the investigation, in both qualitative and quantitative terms, of the role of technology in the productivity of highway construction over the years in the U.S.

Chapter Two begins with a brief review of the economic concepts and tools pertinent to the analysis of technology and productivity and their change over time; this is followed by a review of related research in the highway field itself, including a series of case studies evaluating alternative technical packages for highway construction and some models for evaluation of alternative designs for highway projects. The literature cited in these reviews, as well as all other references cited in the main body of this study, are given in Appendix A. Drawing upon the literature reviewed in the first two sections, the final section of Chapter Two outlines the method of approach to be followed in the research; a two-step approach is developed: (1) stage-level analysis, wherein each stage is considered separately

in the analysis of technology and its change; and (2) project-level analysis, wherein the stages are brought together to form various projects such that the interaction of design and technology in highway construction and operation might be taken into account.

Chapters Three and Four, then, respectively present and discuss the results of the research, each being divided into two parts, the first covering the stage-level and the second the project-level analysis. Before giving the results in each part, Chapter Three covers some largely definitional points pertaining to the level of analysis and briefly describes the actual collection and preliminary work-up of the data. Further details pertaining to the data collection and analysis procedures, as well as presentation of the basic data and some results, can be found in Appendices B and C.* Included with the comprehensive discussion of the results given in Chapter Four is the identification of the potential implications of the study's findings for both the U.S. and developing countries. The presentation of the conclusions and recommendations for further research in Chapter Five completes the study.

*A limited number of copies of Appendices B and C are available upon request.

CHAPTER 2

RESEARCH APPROACH

It is the purpose of this chapter to outline the method of approach employed in this research. It is appropriate to begin with a brief review of some of the literature in the area of technology, productivity, and factor proportions, starting with some of the more general theoretical and macro-study approaches used in a range of industries and ending with some more specific, applied micro-studies in the highway field itself. The final section of the chapter discusses the research approach pursued in the study at hand, in particular the application of some of the methodologies reviewed.

Almost as vast as the array of literature, pertaining to the topics of technique and technology, technical and technological change, and production function and isoquant, is the level of confusion regarding the terminology (27). For the purposes of the research at hand, a certain number of terms and interpretations are necessary. Technical package is used to refer to any factor or resource mix (i.e., labor, equipment, and materials) which can produce a given product (e.g., excavation and hauling of soil twenty feet or gravel surfacing). Technology is defined as the pool of knowledge pertaining to the production of a given product or, alternatively, as the complete set of existing technical packages which can produce this product; often, too, and particularly for the purposes of the research at hand, technology also has a time dimension, such as the

1920's technology of gravel surfacing. Production set is the full set of technical packages representing a particular technology; all existing efficient and inefficient packages are included in this set. Production function is taken as the set of efficient technical packages of a particular production set; that is, those technical packages which produce the most output for the least input. Production isoquant, then, is a part of a production function in that it represents a given amount of a given product. Best-practice technical package is that package which is least-cost when factor prices of a particular period are applied to the resource requirements of the efficient set representing a particular technology.

Finally, technological change relates to the development, due to improved knowledge, of a new set of technical packages which can produce a given product (i.e., a new production function or isoquant) and again to a new time period, such as the technology of the 1950's as opposed to that of the 1920's. Technical change, on the other hand, relates to changes amongst available technical packages or to factor substitution (i.e., a movement along the production isoquant) due to altered factor prices. The term technology change, then, refers to the complete process of changing from a particular technical package, the best-practice one, in one time period to that of a new one, a process which may include both technological and technical change; movements over time of best-practice technical packages thus represent technology change.

2.1 Brief Review of Studies of Productivity and Technology in Other Industries

The identification and more particularly the measurement of technology change in a quantitative sense is an elusive concept which has long plagued economists and engineers alike. Factor productivity, in one form or another, is the oldest and probably still the most commonly used indicator of technology change, and consequently is the first approach generally mentioned by authors reviewing the subject (12, 47, 50, 52, 53, 58). Single factor indexes, defined as average product output per unit of input such as labor or capital, are of limited usefulness in that their dynamic behavior is difficult to interpret. Leaving aside for the moment the problems inherent in measuring inputs and outputs, a change in the index may indicate technological change but it may, alternatively or at the same time, indicate a change in the use of the other factors of production as well as the factor being measured (i.e., technical change).

Multifactor indexes, defined most often as average product output per unit of combined labor and capital input, make up the second and perhaps more useful form of productivity indexes. It was in the late fifties and early sixties that the use of these multifactor productivity indexes in a variety of forms was developed by people like Abramovitz, Solow, Fabricant, and Kendrick. Nadiri (58), as well as others, cites Kendrick's arithmetic measure and Solow's geometric index as the two most often used in empirical research. Kendrick implicitly assumes a homogeneous production function and the Euler condition to obtain the following measure of total productivity change:

$$\frac{dA}{A} = \frac{X_1/X_0}{(wL_1 + rK_1)/(wL_0 + rK_0)} - 1$$

where X = product output

L = labor input

K = capital input

Subscript 1 = current period

Subscript 0 = base period

w = wage rate, changing over time

r = rate of return on capital, changing over time

Solow, in turn, essentially assumes a Cobb-Douglas production function with constant returns to scale and autonomous and neutral technological change and derives the following relation:

$$\frac{dA}{A} = \frac{dX}{X} - \left[\alpha \frac{dL}{L} + \beta \frac{dK}{K} \right], \alpha + \beta = 1$$

where dX, dL, dK - time derivatives of X, L, K respectively

α = share of labor in output

β = share of capital in output

It is Brown's (12) observation, however, that the use of moving weights for combining labor and capital as in Kendrick's measure results in an underestimate of the productivity index because change in

efficiency, an important aspect of technological change, has no effect on the index. As for Solow's measure, Brown presents an even simpler form:

$$\frac{dA}{A} = \frac{d\chi}{\chi} - \beta\frac{d\kappa}{\kappa}$$

where $\chi = X/L$

$\kappa = K/L$

He, among others, still has serious reservations about the measure, however, because of Solow's assuming away all technological change except pure efficiency, although some of it is done with some justification. Nadiri (58), Kennedy and Thirlwall (47), and others cite three possible sources of bias in the use of $\frac{dA}{A}$ as a measure of technological change: (1) the particular form of the production function governing the relation; (2) errors in the measurement of labor and capital and changes in their quality; and (3) relative importance of variables other than labor and capital (e.g., entrepreneurial ability) not included in the measure.

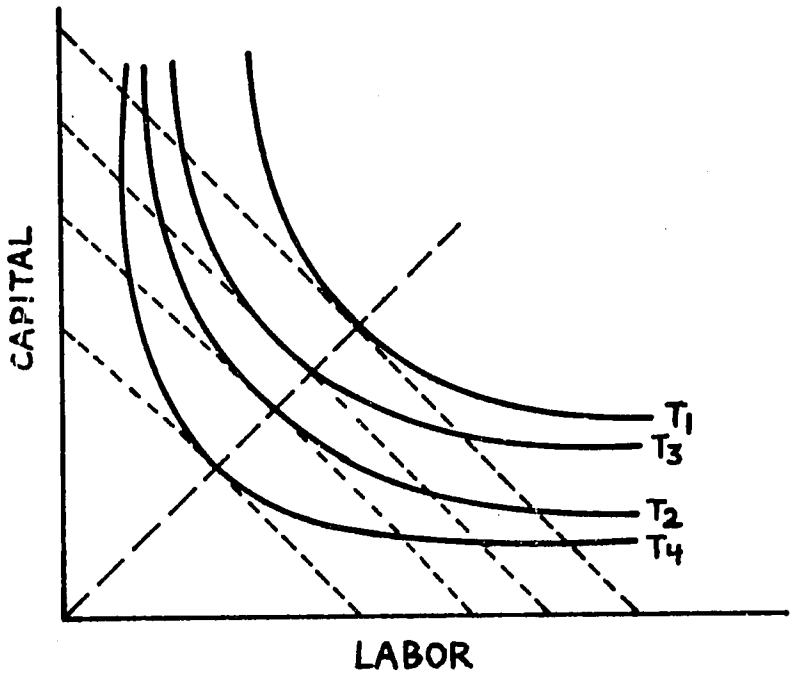
The methodologies discussed thus far have been concerned solely with measuring the change in factor productivity; that is, the change in output not accounted for by changes in inputs, frequently termed the residual and used as a measure of technological change. Salter (73) is probably the first person to make a concerted effort to divide the residual into its component parts. Before proceeding with Salter's analysis,

however, it is appropriate to review the general economic characterization of technology and its change as it is discussed by several authors (12, 58, 73). Measures of efficiency, returns to scale, factor bias, and elasticity of factor substitution are the four standardly cited characteristics of a technology and can be conveniently expressed in terms of a production function. The first two are classified as neutral properties in that they affect labor and capital equally; the last two are termed non-neutral properties since they affect the inputs in a biased manner in the sense, for example, of being labor-saving or labor-using.

According to Brown (12), "the efficiency of a technology determines the output that results for given inputs and given the other characteristics of an abstract technology....[The] efficiency characteristic is a scale transformation of inputs into output." Increased efficiency brought about by technological advance, then, results in equal, in a relative sense, across-the-board, factor productivity increases or unit cost decreases. It can be depicted by parallel shifts of the production isoquant toward the origin, such as a shift from T_1 to T_2 in Figure 2.1a, where the T's represent different technologies producing the same amount of output.

Brown (12), in turn, defines technologically-determined returns to scale as "the extent to which a proportionate change in inputs generates a proportionate change in output due to technology and not the scale of operations of the firm." A technology exhibits increasing returns to scale, or economies of scale, for example, if, for a given proportional

Figure 2.1a: Schematic representation of three forms of technological change.



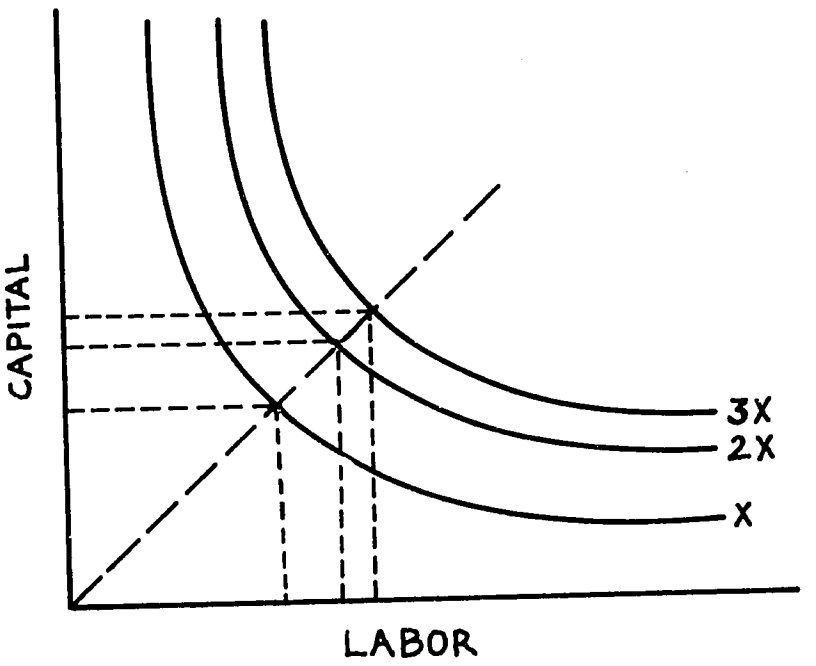
<u>Note</u>: Production isoquants T_1 through T_4 represent different technologies producing the same amount of output.

A shift from: T_1 to T_2 demonstrates increasing efficiency.

T_1 to T_3 demonstrates capital-using bias.

T_1 to T_4 demonstrates decreasing elasticity of factor substitution.

Figure 2.1b: Schematic representation of increasing returns to scale.



Note: The production isoquants represent the same technology but increasing levels of output, beginning with X units near the origin out to 3X units.

increase in all inputs, output is increased by a larger proportion; Figure 2.1b, where the isoquants represent the same technology but increasing levels of output as they move away from the origin, thus demonstrates economies of scale. Technological change, then, may alter the returns to scale characteristic of a set of technical packages, changing it perhaps from decreasing to constant returns to scale.

Factor bias* is most readily defined in a comparative context; that is, given constant elasticity of substitution and relative factor prices, the technology with the higher capital-labor ratio is the more capital-intensive and exhibits a capital-using bias. Bias in technological change denotes greater savings in one input than in the other for all technical packages. A change in the position of the isoquant, more toward one axis than the other, thus represents such bias; that is, a move from T_1 to T_3 in Figure 2.1a results in a proportionately greater increase in the productivity of labor than of capital for all technical packages.

The fourth and final technological characteristic is elasticity of factor substitution; it measures "the ease of exchanging factors of production in the course of the production process" (58) and "thus the extent to which changing factor prices influence best-practice techniques"(73). Elasticity of factor substitution is represented by the degree of curvature of the production isoquant; that is, a movement of the isoquant from T_1

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*There is considerable controversy over the definition of factor bias, the two primary schools of thought being Hicks and Harrod, the above definition being basically Hicks; for further discussion see references 47, 58, 72, 73.

to T_4 depicts a decrease in the ease of substitution. Two limiting cases are evident: (1) a right-angle isoquant which has an elasticity of zero and on which factor prices have no influence; and (2) an isoquant approaching a straight line which has an elasticity approaching infinity and on which factor prices have a substantial impact.

There is much discussion throughout the literature (14, 47, 58, 73) of the case of non-neutral change in technology, and the fact that, in most developed countries at least, increases in labor productivity over time have generally been greater than those in capital productivity. Two explanations are commonly presented: (1) technological advance is inherently biased toward labor-saving; and (2) technological advance is largely unbiased but substitution is induced by technological progress in the manufacture of capital goods. Arguments for both views abound, but relatively little progress has been made toward a definitive settlement of the issue.

The nature of the technology itself, as depicted by the technological characteristics discussed above, and relative factor prices are commonly recognized as the primary determinants of factor productivity. In combination, these factors determine the best-practice technique for any particular period. Movements over time of the best-practice technique, then, represent technology change, and it is this which Salter (73) tries to decompose. He begins by assuming constant returns to scale over the range of capacity outputs being considered and then defines quantitative measures for the remaining technological characteristics.

His first parameter is technical advance which measures the rate of

movement of the production isoquant toward the origin, basically looking at the effects of efficiency, as defined above, on unit costs. Formally defined, "the extent of the technical advance from one period to another is defined and measured by the relative change in total unit costs when the techniques in each period are those which would minimize unit costs when factor prices are constant" (73); that is:

$$E = \frac{L_{n+1}w_n + K_{n+1}g_n}{L_n w_n + K_n g_n} \quad \text{for the discrete case, and}$$

$$E_r = \frac{wdL + gdK}{Lw + Kg} \quad \text{for the continuous case}$$

where Subscript n = initial period

w = wage rate

g = price of capital services

dL, dK = time derivatives of L, K

Subscript r = proportionate rate of change, e.g., $E_r = dE/E$

<u>Note</u>: Either period's prices can be used in the discrete case, each giving a slightly different result, due to the inevitable index-number ambiguity problem.

Salter's second parameter is that of factor bias as defined above. Formally, "the labor or capital-saving biases of technical advance are

measured by the relative change in capital per labour unit when relative factor prices are constant" (73); that is:

$$D = \frac{K_{n+1}/L_{n+1}}{K_n/L_n} \qquad \text{for the discrete case, and}$$

$$D_r = \frac{d(K/L)}{K/L} \qquad \text{for the continuous case}$$

<u>Note</u>: $D < 1$, $D_r < 0$, capital-saving bias

$D = 1$, $D_r = 0$, neutral or no bias

$D > 1$, $D_r > 0$, labor-saving bias

His third parameter is elasticity of factor substitution, which is important in determining the effectiveness of changes in relative factor prices in increasing or decreasing the rates of productivity increase established by technological change alone. Elasticity of substitution "measures the proportional change in capital per head in response to a small proportionate change in the relative marginal products (or factor prices) of labour and capital" (73); that is:

$$\sigma = \frac{d(K/L)}{K/L} \cdot \frac{w/g}{d(w/g)} ,$$ measured at a point on each production isoquant appropriate to the measures of E and D.

Salter finally combines these three parameters to yield a quantitative description of the growth of best-practice productivity in terms of the nature of technological change and changing factor prices. The rate of change of unit labor and capital requirements are thus:

		technical advance effect		bias effect		substitution effect
L_r	=	E_r	-	πD_r	+	$\sigma\pi(g/w)_r$
K_r	=	E_r	+	$(1-\pi)D_r$	+	$\sigma(1-\pi)(w/g)_r$

where π = share of capital costs in total costs

Salter criticizes his own work from the standpoint that the measures represent a drastic and only approximate summary, resulting in such difficulties as the index-number problem inherent in such work and the failure to consider returns to scale, although he does propose a means to alleviate this latter simplification. Brown (12) sees Salter's work as producing well thought out measures, but questions their applicability due to the difficulty of holding each constant while measuring the others. Little empirical testing of these measures has been done, although in the second part of his book Salter does perform an analysis of a range of British and American industries; in this he concludes that neutral technological advances and potential and realized economies of

scale are primarily, and factor substitution less so, responsible for the differing rates of labor productivity increase in the industries studied.

The production function, a tool repeatedly mentioned above particularly in conjunction with factor productivity indexes, constitutes yet another approach to the analysis of technology and its change, as reviewed by various authors (12, 47, 50, 58). Dating back nearly fifty years, the Cobb-Douglas production function is probably the most famous, noted for its simplicity in terms of both understanding and applying it and for its possession of certain desirable neoclassical properties (e.g., it does not specify a priori the returns to scale). It was not until about twenty years ago, however, that the Cobb-Douglas function was used in the measurement of technological change. The two-factor Cobb-Douglas production function in its unrestricted form is:

$$X = AL^{\alpha}K^{\beta}$$

where A, α, β = constants to be determined empirically

The technological characteristics, as defined above, can be expressed by various combinations of the empirically determined parameters of the function. A change in the parameter, A, thus indicates a change in efficiency. The sum of the partial elasticities of production, α and β, is an indicator of the returns to scale characteristic (i.e., $\alpha + \beta < 1$ indicates decreasing returns to scale; $=1$, constant; and > 1, increasing).

The ratio of these same two parameters indicates the factor bias of the technology represented by the Cobb-Douglas function; an increase in β relative to α, for example, demonstrates a capital-using technological change. The fourth and final characteristic, elasticity of factor substitution is fixed at unity in any Cobb-Douglas relation, a feature which severely restricts the applicability of this production function.

Some fifteen years ago a more general form of a production function was developed, the Constant Elasticity of Substitution (CES) function, in which the elasticity of substitution is held constant for any particular technology but can change as technology changes. The CES relation has the basic properties of a neoclassical production function and includes the Cobb-Douglas function as a special case. The two-factor CES production function is:

$$X = \gamma\,[\delta K^{-\rho} + (1-\delta)L^{-\rho}]^{-\mu/\rho}$$

where $\gamma, \mu, \delta, \rho$ = constants to be determined empirically

As in the case of the Cobb-Douglas relation, the characteristics of any technology can be expressed in terms of these empirically determined parameters. An increase in γ represents an upward shift in efficiency; the value of μ indicates the degree of returns to scale, and a change in μ may be attributable to some change in technology. As for the non-neutral technological characteristics, the factor bias parameter is δ,

which is defined over the interval 0 to 1 and measures the extent to which the technology is capital-using; the elasticity of factor substitution, σ, is represented by $1/(1+\rho)$ in the CES relation, a change in σ indicating a change in technology.

Attempts to use aggregate production function theory in the estimation of total factor productivity or the parameters representing the characteristics of technology and its change have encountered various difficulties and criticisms, which have often been countered with potential solutions. The data base for such studies is generally an industry as a whole or even the entire economy of a country, which leads to many problems in the measurement of factor inputs and product outputs. The factors of production and the products themselves are heterogeneous elements with divergent characteristics, and yet they are standardly aggregated into labor and capital inputs and a single output. In an effort to avoid measuring capital, which has to be done in value terms, Johansen and others, cited by various writers (1, 47, 50, 63), have derived indirect production relations requiring at most a measure of the elasticity of output with respect to capital. An aspect of labor and capital conventionally ignored is that of quality, resulting in changes in factor quality potentially being responsible for a large share of the change in total factor productivity. Attempts to deal with this issue have gone in three directions: (1) models of capital-embodied technological change have been developed (12, 47, 52, 58); (2) the idea of quality adjustment of labor has been pursued by Denison, Griliches, and Kendrick, among others

(47, 58, 107); and (3) the growth accountancy approach has received attention from Denison, Jorgenson, and Griliches, among others (12, 47, 50, 58, 107). One final area of controversy pertaining to the data base is the type of data series used, time-series or cross-sectional, each having its own particular problems (9, 12, 47, 58, 63).

The other major area of difficulties and criticisms, encountered in efforts to use aggregate production function theory in the study of technology and its change, has centered around the limited flexibility of the functional form and difficulties in fitting it to available data. The use of simplifying, often unrealistic assumptions, such as perfect competition in factors and goods markets, constant returns to scale, and entrepreneurs' instantaneous adjustment to exogenous price changes, are a major point of contention (9, 47, 58, 63, 114). Moreover, the form of some of the more common production functions is such that the sources of factor productivity cannot be adequately separated and identified (8, 12, 58, 63). The outcome of this has been the development of more generalized production functions, such as the Variable Elasticity of Substitution (VES) relation, to handle cases where the elasticity of substitution is sensitive to changes in factor proportions, and the Constant Difference Elasticities of Substitution (CDS) relation, to handle cases with more than two factors of production (8, 58, 63). Simultaneity and nonlinearities between the production function and marginal productivity conditions have led to problems in estimation, resulting in the development of new, often less restrictive, estimating techniques (9, 58).

It thus seems that considerable progress has been made in the theory and estimation of aggregate production functions, but empirical evidence on the performance of these new functions and estimating techniques is scanty. Little can be said except that production function based estimates of total factor productivity and parameters of technological change are very sensitive to slight changes in the data, the specification of the production function, and the method of estimation (9, 47, 52, 58, 63). Feelings about the usefulness of the aggregate production function in the analysis of technology and its change range from Brown (12) who strongly supports it, to Nadiri (58) who feels little further progress can be made until the available data is improved, to Acharya et al (1), Baer (6), Bhalla (9), and O'Herlihy (63) who believe a micro-study approach is the route to follow rather than the macro-study approach of the aggregate production function.

As is evident from the above discussion, the economic literature tends to be largely theoretical in nature, and even when the theory is put to a test, it is generally at the aggregate level of an industry or country. In recent years, however, micro-studies at the firm or even process level have begun to come into their own as a means of studying technology. Chenery (17, 18), as long ago as the late forties, introduced the idea of the engineering production function. This is a mathematical statement connecting the physical variables and the output of a process; it can be translated into an economic production function, which relates inputs and outputs in economic rather than physical terms, potentially

yielding the isoquants, expansion paths, and cost curves generated by more conventional economic analysis. Its advantages include its being a more explicit representation and analysis of technology and its change, and its not being restricted to observable input combinations. Its disadvantages are that it requires a thorough understanding of the physical technology and is restricted to relatively simple processes, and the range of alternatives is somewhat limited (e.g., fluid transport through pipelines rather than via any mode of transport) (17, 18, 20, 48, 50, 65).

The difficulties inherent in the macro-studies discussed above have thus resulted in a rekindling of interest in this more micro-study or case study approach. It is Sen's observation, in the Foreword to Bhalla's book (9), that this has particularly been the case in the study of choice of technology in developing countries, where the informational dichotomy between the planning and operations level has necessitated it. This is, the planners tend to stress the macro-economic effects of alternative technical packages, greatly simplifying the technology itself, whereas the operations personnel do the opposite; for many years, the emphasis has been on the planning side, but it now seems appropriate to switch the emphasis to operations. Such micro-studies basically entail observing and recording the inputs required for and influences impacting the various stages of production, for alternative means of producing a given output; this data may then be used to synthesize a production isoquant for the good. The advantages include close interaction with engineering data and freedom from the confines of mathematically tractable production

functions; the disadvantages include its being expensive and its yielding results which cannot readily be generalized and with no convenient summary measures (1, 6, 9). This shifting in emphasis on the nature of research in the analysis of technology has led to works like Cowing's (20) and Pearl's and Enos' (65) recent applications of the engineering production function, the case studies presented in Bhalla (9) and reviewed in Baer (6), and the array of literature pertaining to highways presented in Section 2.2.

2.2 Brief Review of Related Research in the Highway Field

There are two classes of studies pertaining to highways and their analysis that are directly relevent to the research at hand. Those of the first group, which are reviewed in some detail in Section 2.21, investigate the technical and economic feasibility of alternative technical packages for construction, primarily in conjunction with one design and looking only at construction costs, but being very concerned with deriving accurate and detailed resource productivity and cost data. Those of the second class, which are reviewed only briefly in Section 2.22, investigate the trade-offs among construction, maintenance, and user costs of alternative designs, with the construction technology generally being implicit in the rather aggregate cost and/or productivity data used in the analysis. In the analysis of technology and its change in highway construction, what is ultimately needed, and is used in the study at hand, is a combination of the two efforts, due to the complex interaction of design and technology in highway construction and use.

2.21 Some Case Studies Evaluating Alternative Technical Packages for Highway Construction

With the importance of analytic work based on economic and engineering analyses of individual industries, projects, and processes recognized and research of this type becoming increasingly common, as noted toward the end of Section 2.1, it is this micro-study or case study approach that is reviewed here, as it has been used by numerous authors to study the issue of choice of technology in highway construction, primarily in the context of developing countries. The area of labor-capital substitution in public works construction was a relatively dormant one from the early 1960's to the early 1970's, when interest was again aroused due to its potential for the creation of employment in the developing countries. The studies reviewed here represent the major efforts in the highway field in the seventies, as well as a couple dealing with earthmoving activities from the early sixties that provide some of the groundwork for the more recent studies (see Table 2.1).

The overall objective of this group of studies is to establish the technical feasibility of alternative technical packages for road construction, and, in turn, to relate these technically feasible alternatives to relative factor scarcities such that their economic feasibility can be determined under various institutional and environmental conditions. The majority of the studies, in pursuit of this objective, apply the factor productivity and price data they have collected to one or more real or hypothetical road (dam and canal in the case of Dreiblatt [24]) construction projects and parts thereof in order to determine the economic

Table 2.1: A list of the case studies which are reviewed.

Code Name (Reference Number)	Title of Study	Countries	Year Published
UN (83)	Capital Intensity in Heavy Engineering Construction	United States	1958
(84)	Capital Intensity and Costs in Earth-Moving Operations	United States, Europe, Asia and the Far East	1960
(85)	Earthmoving by Manual Labour and Machines	Asia and the Far East	1961
Dreiblatt (24)	The Economics of Heavy Earthmoving	India, West Pakistan[a]	1972
Müller (57)	Labour-Intensive Methods in Low-Cost Road Construction: A Case Study	A country in Subtropical Africa	1970
IBRD-I (42)	Study of the Substitution of Labor for Equipment in Road Construction, Phase I: Final Report	Various countries	1971
IBRD-II (41)	Study of the Substitution of Labor and Equipment in Civil Construction, Phase II: Final Report	India, Indonesia	1974
IBRD-III (38)	Scope for the Substitution of Labor and Equipment in Civil Construction: A Progress Report	India, Indonesia, Kenya, Honduras	1976
(39)	Study of the Substitution of Labor and Equipment in Civil Construction, Phase III: Technical Report No. 1	India, Indonesia	1974
(40)	World Bank Study of the Substitution of Labor and Equipment in Civil Construction - Technical Memorandum No.1-25	India, Indonesia[a]	1975-76
IBRD-Indonesia (37)	Iron Deficiency Anemia and the Productivity of Adult Males in Indonesia	Indonesia	1974
ILO-Thailand (45)	Thai Workers in Heavy Road Construction Activities - An Ergonomic Pilot Study	Thailand	1974

(Table 2.1 continued)

Code Name (Reference Number)	Title of Study	Countries	Year Published
ILO-Iran (44)	Roads and Redistribution, A Social Cost-Benefit Study of Labor-Intensive Road Construction Methods in Iran	Iran[a]	1973
ILO-Philippines (43)	Men or Machines, A Philippines Case Study of Labour-Capital Substitution in Road Construction	Philippines	1974
ILO-Nepal (69)	Comparative Evaluation of Road Construction Techniques in Nepal	Nepal	1973
Vaidya (111)	The Choice of Technology in Highway Construction Industry - A Case Study of Nepal	Nepal	1974

[a]Data used in at least some of the analysis came from various countries.

feasibility of the various technically feasible alternatives observed. IBRD-I (42) and IBRD-II (41) represent a major portion of the work in the productivities area, although several other studies including Dreiblatt (24), Müller (57), and Vaidya (111) also focus more on resource productivities than prices. ILO-Iran (44), ILO-Philippines (43), and ILO-Nepal (69), on the other hand, are largely concerned with deriving various sets of factor prices, which may more truly reflect relative factor scarcities in a developing country than do the prevailing market prices; these studies are thus able to additionally investigate how the economic competitiveness of alternative technical packages varies with factor price.

IBRD-III (38, 39, 40), one of the exceptions to the basic procedure, is largely concerned with devising means to improve labor productivity; it thus tends to focus on factor productivities and prices at the disaggregate activity/task level, although it does consider some project-level implementation in its demonstration projects and studies of broader issues like management and organization. The UN studies (83, 84, 85) can also be singled out due to their concentration on resource productivity and unit cost at the task-level without ever aggregating it to the project level. The last two studies, IBRD-Indonesia (37) and ILO-Thailand (45), concentrate exclusively on factor productivities, in that they are studies of the relationship between health, nutrition, and general physical condition of the workers and their productivity.

The case study approach to the analysis of labor-capital substitution

in highway construction may entail three basic activities: (1) collecting the data; (2) applying it to one or more real or hypothetical road construction projects or parts thereof; and (3) analyzing the results. The data required for these studies consists of alternative technical packages for road construction activities, tasks, or stages, and the resource productivities and costs of these packages under various institutional and environmental conditions. The general paucity, lack of detail, and questionable reliability of the data in the engineering and economic literature and the important impact of institutional and environmental conditions on productivity and cost, as revealed by IBRD-I (42) and UN (83, 84, 85) among others, led to the use of field studies and project records in one or two countries in most cases. This is particularly true for the more labor-intensive packages, and efforts were thus largely concentrated on these. As for the equipment-intensive packages, it is felt that better records are generally kept, and thus more reliance is placed on the data already available, in some published form or in the form of contractor's and project records. Both the IBRD (IBRD-I [42], IBRD-II [41], and IBRD-III [38, 39, 40]) and UN (83, 84, 85) studies consider a large number of alternative technical packages for various construction activities or tasks, while the other cases are somewhat more limited in scope.

The case studies exhibit a broad range in emphasis on collecting and analyzing productivity data. Dreiblatt (24), for example, after mentioning the importance of institutional and environmental considerations,

ignores them completely in his comparative analyses; ILO-Nepal (69) and Vaidya (111) consider them in a rather qualitative, descriptive manner, although ILO-Nepal does at least use a frequency distribution, rather than a single value, to express the quantity of each factor required for a given output in the hilly regions. Some of the other studies, such as ILO-Iran (44), ILO-Philippines (43), and, to a lesser extent, IBRD-I (42) and UN (83, 84, 85), specify at least some of the institutional and environmental parameters in association with productivity figures for various activities and tasks and consider them in the analysis of alternative technical packages. ILO-Iran (44), for example, develops a production model for each task and technical package, in which a normal productivity is specified with percentage adjustments for changes in work and team factors such as earth type and labor quality.

Finally, the most sophisticated, and only statistically-based, approach is that of IBRD-II (41) which is extended somewhat in IBRD-III (38, 39, 40). A large share of the IBRD's efforts are concentrated on quantifying the relationships among resource inputs, product outputs, and various institutional and environmental parameters for various construction activities and tasks. A generalized Cobb-Douglas type specification fit by regression is used to model these relations, the data base being field observations of on-going civil construction activities and tasks. The data requirements for this are substantial, however, and so far it has been done for only a few parameters, some of the more important activities and tasks, and the more labor-intensive technical packages;

moreover, the particular functional form is being investigated in IBRD-III (38, 39, 40). In the specific area of quantifying the relationships between the general physical well-being of the workers or animals and their productivity, IBRD-Indonesia (37), ILO-Thailand (43), and a few of the technical memorandums in IBRD-III (40 - Numbers 4, 11, 21) make certain contributions.

In addition to factor productivities, factor prices are necessary in order to convert the physical productivities to unit costs to be used in an evaluation of the economic feasibility of alternative technical packages. In all of the cases dealing with one or two countries, and even in the case of IBRD-I (42) which gathers productivity data from a variety of countries, a prevailing, or market, hourly cost is determined for each of the various resources. In the case of labor, this is quite straightforward, the local wage rates for different types of labor, although there is some discussion concerning such costs as provision of amenities and transport for labor and mobilization of labor and whether they should be incorporated here or in the project overhead, with the frequent result that they are ignored. Hourly equipment costs are more complicated to derive, being made up of ownership costs such as interest, depreciation, and maintenance and repair labor and materials and operating costs such as equipment consumables, tires, and operating labor. Assumptions as to equipment life and utilization and maintenance and repair facilities, which are often very different in developing countries than in the developed ones, have an important influence on the hourly cost;

there is even some disagreement over what should be included in the capital cost of a piece of equipment, let alone its hourly cost.

A perhaps more interesting area of difference of opinion pertaining to factor prices is the use of alternative pricing schemes.* The UN studies (83, 84, 85) just gloss over the factor prices issue, looking at productivities and unit costs for the alternative technical packages, while Dreiblatt (24) and Müller (57) apply a single set of factor prices, those estimated to be prevailing, to their productivity data; all three, however, recognize the possibility of using shadow prices. The IBRD studies (IBRD-I [42], IBRD-II [41], and IBRD-III [38, 39, 40]) and Vaidya (111) also use a single set of prevailing labor and equipment prices, but they then perform a sensitivity analysis on the price of one or both resources. Sensitivity analysis in conjunction with a cost minimizing production routine, like that used in IBRD-II (41) or proposed in Vaidya (111), can be used to derive the production isoquant for a particular output. In IBRD-I (42), a breakeven wage rate,** defined for a given set of

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*Prevailing or market costs of resources are those costs actually incurred in any business transaction. In many developing, and even developed, countries, however, these costs may diverge from their true social costs, in which case such resources may be shadow priced to more truly reflect their relative scarcity as well as perhaps certain developmental objectives.

**Breakeven wage rate: $W = (E_1-E_2)/(L_2-L_1)$, where E = equipment cost, L = unskilled labor hours, and subscript 1 denotes equipment-intensive technical package and 2 labor-intensive; W also represents the marginal rate of substitution of equipment for labor under these assumptions.

equipment prices as that unskilled wage rate at which the cost of executing an activity by labor is identical to that by equipment, is often used to look at the trade-off between equipment and labor in various construction activities, tasks, and stages.

It is the three ILO studies (ILO-Iran [44], ILO-Philippines [43], and ILO-Nepal [69]) that really focus on the relative factor prices issue, much as the IBRD's work focuses largely on factor productivities. Because market prices prevailing in developing countries do not always properly reflect relative factor scarcities, various sets of input prices, which reflect different approaches to the question of optimal allocation of resources available to an economy, might be feasible and should be investigated. Using established methods for deriving shadow prices (basically those of UNIDO [23], OECD [51], and a mix of Sen [74] and UNIDO [23]) and varying certain assumptions which ultimately influence the relative input prices, the ILO studies (43, 44, 69) try various sets of labor and equipment prices in conjunction with their productivity data in order to investigate variations in the economic competitiveness of alternative technical packages with factor prices.

Given that the data has been collected, the final two steps to any case study entail applying the data to one or more real or hypothetical road projects or parts thereof and analyzing the results, and are best discussed concurrently. The UN studies (83, 84, 85) are rather limited in this regard in that only a couple of earthmoving tasks are considered, and the economic analysis is simply a tabular/graphical comparison of their

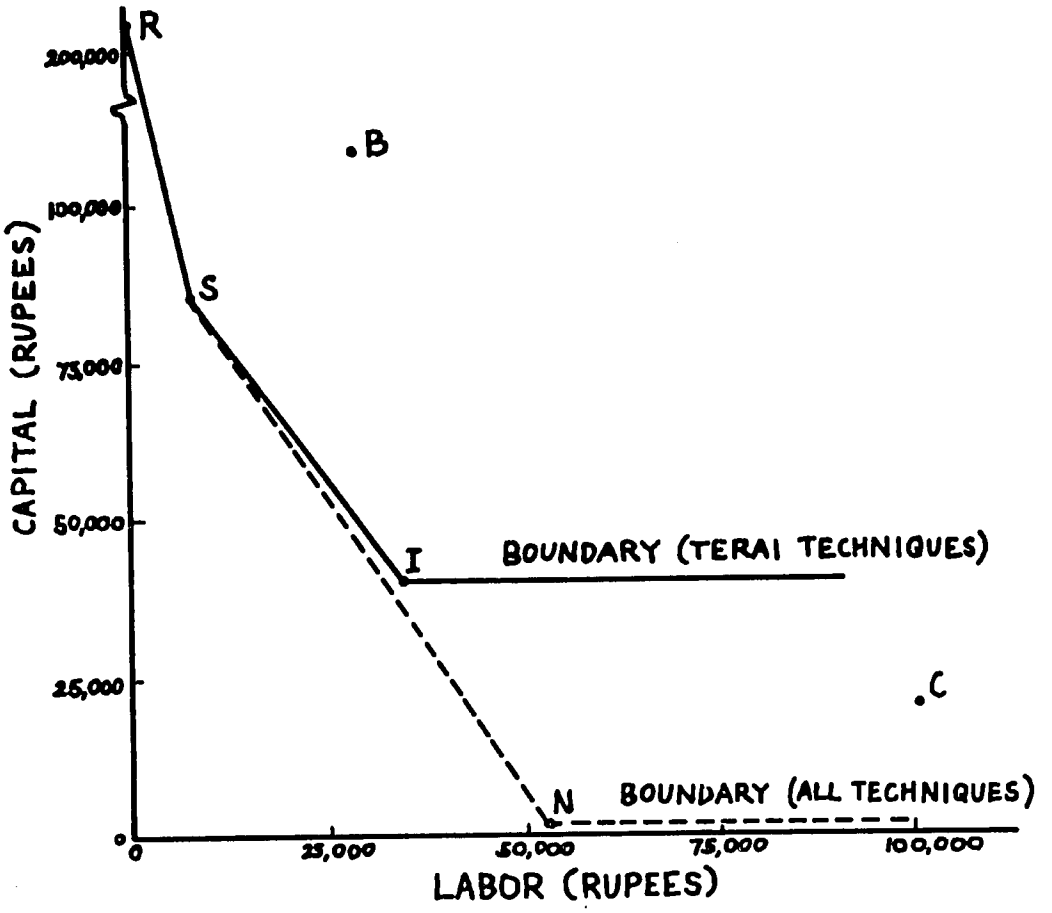
unit costs when various technical packages are used under a few varying environmental conditions. The primary difficulty with these studies is that the data is from a wide range of countries and projects, resulting in a wide variety of unmeasured institutional and environmental factors. Some of the other studies, such as ILO-Philippines (43), IBRD-II (41), and IBRD-III (38, 39, 40), do a similar type of analysis at the activity/task level, but their data is limited to one country, and thus the variability of unmeasured influences should be less.

In the cases of Dreiblatt (24), Müller (57), and ILO-Philippines (43), a wider range of activities/tasks is studied as well as the product, road, dam, or canal, they produce. The basic steps involved are as follows: (1) activities/tasks in the project are identified, and their quantities estimated; (2) for each, a capital and labor-intensive, and in ILO-Philippines (43) sometimes a modified labor-intensive, technical package is defined, and its resource requirements determined; (3) each package is then priced (with market and shadow prices in ILO-Philippines [43]), and comparisons can be made at the activity/task level; and (4) the activity/task costs are then summed for each category of technical packages, except in the case of Müller (57) who also sums over a combination of the capital and labor-intensive packages, and comparisons can be made at the project level. Although this method gives the costs of the various technical packages alone and in combination, it says nothing about their relative efficiencies. Still, it is straightforward to use and reasonably useful as long as the number of activities/tasks and

categories of technical packages is limited, or there is limited interest in mixing the packages of the various technical categories.

ILO-Nepal (69) and Vaidya (111) pursue the same basic approach, with some exceptions and extensions. These two studies are somewhat different from the other cases reviewed here, in that they are based on five different projects in Nepal, each constructed by a different country with its own particular set of technical packages, ranging from the highly labor-intensive practices of the Chinese to the highly capital-intensive ones of the Russians. Resource inputs for a given unit of output have been gathered at the stage level for each project, and a single set of quantities is used to aggregate the stages, representing one set of technical packages or a mix, to a standard kilometer of road. The validity of such comparisons is necessarily constrained by differences among the projects, some of which could be alleviated, but others of which could only be qualitatively described; for example, road design and quality which will later affect maintenance and user costs differ among projects, the environmental and institutional conditions differ, the actual activities/tasks and materials used in the different stages differ, and so forth. As an extension to the above discussed methodology, ILO-Nepal (69) plotted production isoquants in order to determine the relative efficiencies of the alternative sets of technical packages at each stage and in the aggregate (see Figure 2.2 for a sample graph); it also employed a number of matrices (e.g., a technical package, resource price [containing project, standard, and shadow prices], and total cost matrix)

Figure 2.2: Capital and labor inputs of the various technical packages for the earthwork stage of the Nepal projects, valued at standard prices for Nepal (source: ref. 69).



Note:

Project	Total Cost (Rs/10,000CM)
R - Russian	219,352
B - British	137,748
S - Standard[a]	94,421
I - Indian	75,159
N - Nepali	55,457
C - Chinese	121,144

[a]This represents the standard technical package for embankment formation from the UN-HMG Nepal Road Feasibility Study Report (referenced throughout ILO-Nepal [69]) and is included for the sake of comparison.

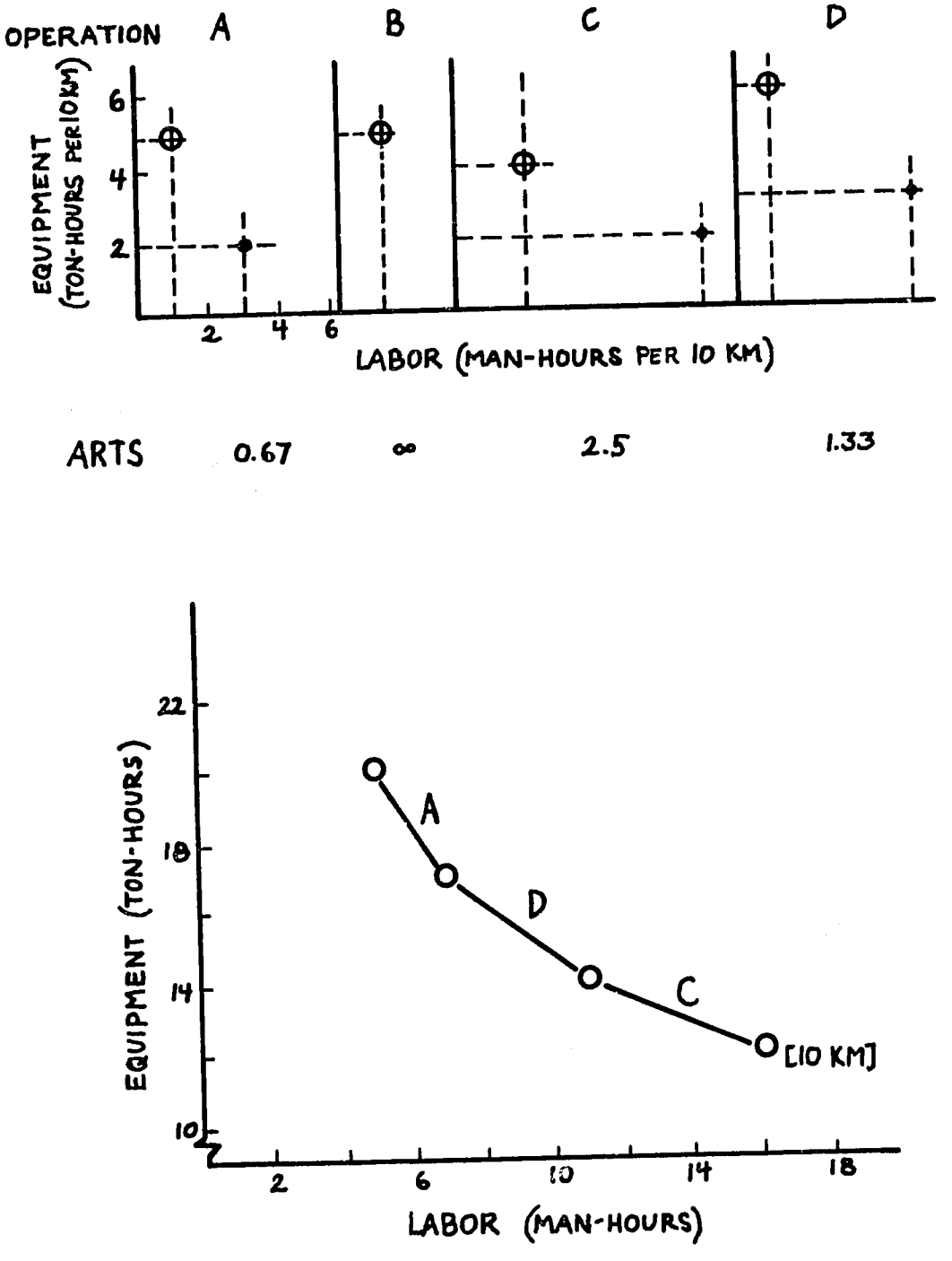
A distinction can be made between the techniques used in terai road construction and those employed in the hills (i.e., Chinese and Nepali projects); in terai road construction, earthwork entails lifting of the embankment material, while in side hill cutting the earth merely has to be pushed over the side of the formation, resulting in earthwork per cubic meter generally being cheaper in the latter case. Two separate boundaries have thus been inserted linking the efficient technical packages (at least efficient relative to those observed); it should be noted that the British technical package is inefficient relative to the other terai techniques, while the Chinese is inefficient relative to the Nepali project.

as an effective means of organizing the data.

Productivities and technical packages are best observed at the disaggregate level of activities or perhaps tasks, while the object of interest is the road itself and the mix of packages to be used in its construction. This aggregation from the activity to task to stage to project level can be accomplished in the additive manner described above; if, however, it is desirable to consider mixing the technical packages at the disaggregate level and to consider only the relatively efficient combinations as is usually the situation, then a production function approach, as employed in IBRD-I (42) and ILO-Iran (44), is more appropriate. The derivation of an aggregate production isoquant is illustrated in notional form in Figure 2.3. ILO-Iran (44) and IBRD-I (42) both use this approach quite successfully for a limited number of technical packages and conditions. ILO-Iran (44), for example, uses it to aggregate eight activities/tasks (those where substitution is possible) to the project level, considering two packages for each activity/task, for five different projects representing various road classes and terrains; it then calculates the average rate of technical substitution for each project as a whole, and finding them all to be about the same, it proceeds to look at the direct employment generated in each case as the labor-intensive activities are substituted for the capital-intensive ones.

There are several difficulties inherent in such aggregation of construction activities. First, it assumes the activities are independent, requiring that activities which are not for certain technical packages

Figure 2.3: Notional representation of the derivation of an aggregate production isoquant (source: ref.44).



(Figure 2.3 continued)

Note: The basic procedure for deriving the aggregate production isoquant is as follows: (1) suppose the construction consists of four operations, A through D, and for all except B there are two technical packages; (2) calculate the average rate of technical substitution of labor for equipment

$$ARTS = \frac{L_2 - L_1}{E_1 - E_2}$$

for the pairs of technical packages using it to rank the packages; (3) beginning with the most capital-intensive package for each operation, sum the resources across the operations and plot this on the production isoquant graph; (4) next, for the pair of packages with the lowest ARTS (A in this case) use the resources of the more labor-intensive package, combining these with the resources of the capital-intensive packages for the other operations (B through D), and plot the sum; and (5) so forth, until all of the labor-intensive technical packages have been substituted for the capital-intensive ones. The result is a production isoquant representing the efficient mixes of packages (efficient relative to those available). In the interests of minimizing cost, it is economically feasible to substitute labor for equipment up to the point where the average rate of technical substitution equals the ratio of the average price of equipment to that of labor; for example, if

$$\frac{P_E}{P_L} = 1.5,$$

then one can economically use the labor-intensive packages for operations A and D and capital-intensive ones for B and C. Alternatively, one might price the points on the isoquant to determine the least cost solution.

In IBRD-I (42), the breakeven wage rate is used instead of ARTS; this is the inverse of ARTS with equipment measured in dollars rather than ton-hours. The major disadvantage of this approach is that the price of equipment cannot be varied as readily, although it eliminates the problem of finding an average price for equipment (a nonhomogeneous set) and the question of what to do with equipment that cannot be measured in ton-hours.

(e.g., labor's productivity in loading depends on the haul vehicle due to the impact of load height) be treated as a single item. Perhaps more importantly, there are certain interdependencies among activities and impacts of substitution that are more subtle and harder to handle (e.g., the effect on equipment's utilization rate of substituting it by labor for a particular activity), and thus it is not clear that optimization on an activity basis is compatible with that on a project basis. Further, each aggregation is restricted to a particular set of institutional, environmental, and design conditions, and the number of possible alternatives is tremendous. Moreover, rather than looking at alternative mixes of technical packages for building one specific road, it is desirable to consider building various roads of equal quality and service, in that a particular technique might be more suited to one design than to another. If one begins to try to incorporate project scale, time, and other constraints such as minimizing foreign exchange cost or taking account of the availability and mobilization costs of labor and equipment, the problem becomes very complex indeed. Even ignoring this, this approach gets rather tedious and difficult to do if there are more than two technical packages for each activity or if the aggregation is done in a stepwise manner.

These types of difficulties and complexities encountered in the aggregation process led to the development of a computerized linear programming model in IBRD-II (41). The objective of this model is to select a set of methods to be used in constructing a given civil works project

(or set of projects) to minimize total cost, subject to the country's available resources and technology. Using the same type of activity/task level data required above, this approach can quickly select the optimum mix of technical packages for a project from a large set of alternatives. Through successive applications of the model, alternative institutional and environmental conditions, project designs, pricing schemes, and so forth can be investigated, all rather quickly; testing the sensitivity of the results to alternative values of various parameters is a prime feature of linear programming models. An aggregate production isoquant can readily be derived by using a continuum of labor prices and solving for the minimum cost solution.

Furthermore, a number of features already incorporated or that could be incorporated in the model help to alleviate some of the difficulties in aggregation discussed above. Resources, for example, may be subject to minimum or maximum constraints (e.g., a minimum might be set on the amount of labor to be employed); new resources incur a set-up cost, while resources already on the site are available for only a limited number of hours during any period; and certain resources can be used only in integer or discrete quantities, an option which might be used to incorporate some features of economies of scale. Time has been introduced into the model through the use of time periods and a discount rate, and a certain limited amount of scheduling of tasks and resources is possible through constraints. The model is, however, still restricted to comparing alternative mixes of technical packages for building a specific road

(i.e., a given set of design standards), rather than building different roads of equal quality and service; the suggestion has been made, however, to use it in conjunction with models, such as those discussed in Section 2.22, which can analyze design standards. This model thus seems a potentially useful tool in the study of alternative technical packages, alone and in various combinations, for civil works construction and warrants further consideration and application, particularly in the field; in IBRD-II (41), for example, it is used only in a single road project and in a set of projects entailing four categories of roads.

In completing the review of this set of a dozen case studies, it seems only appropriate to briefly state their general findings, conclusions, and directions for further research. It is generally agreed that there exists a broad range of possible technical packages for use in highway construction, and that it is technically feasible to substitute labor for equipment in a wide variety of activities. The issue of economic efficiency of alternative technical packages, however, is much less clear-cut: (1) several of the studies, including Dreiblatt (24), Müller (57), IBRD-II (41), and ILO-Iran (44), find that although certain labor-intensive techniques may be efficient relative to the others observed, they are generally not economically competitive at the market prices judged to be prevailing in the study country; and (2) certain other studies, including IBRD-III (38, 39, 40), ILO-Philippines (43), ILO-Nepal (69), and Vaidya (111), on the other hand, find certain of the relatively labor-intensive packages to be economically feasible at market prices. Finally, it is

generally agreed that the application of shadow prices, as demonstrated by the three ILO studies (43, 44, 69), makes the labor-intensive techniques more competitive, often to the point of being socially profitable. Recognizing the necessarily restricted nature of these studies and questions remaining as to appropriateness of market versus shadow prices, the general consensus, with but one exception (Dreiblatt [24]), seems to be that efforts should be expended in the direction of increasing labor's role in highway construction in labor-abundant, capital-scarce countries. It is thus proposed that future efforts be directed toward devising means to improve labor productivity and to effectively implement more labor-intensive practices.

2.22 Some Models Evaluating Alternative Designs for Highway Projects

A shortcoming of the case studies reviewed above is their focusing on alternative means of construction of a single project design, rather than extending the project beyond the construction phase to that of operation, such that various project designs might be investigated in conjunction with alternative technical packages. Considerable progress has been made toward developing a model to evaluate alternative design, construction, and maintenance strategies for low volume roads, in terms of construction, maintenance, and user costs since the mid-sixties, when Soberman (76) made his preliminary, largely theoretical contributions to the field. Lago (49) followed shortly with the development of a model for estimating total road transport costs. Building upon this earlier work, Vance (112) in the late sixties, using the concept of production function based cost

functions, produced a new version of a road transport cost estimating model, one that was suitable for hand calculation and could handle, for example, staging of construction and alternative labor/capital mixes for use in road construction and maintenance. Concurrently, personnel at M.I.T. were developing the first version (36) of the Highway Cost Model (HCM), a computer-based, cost-estimating, simulation model which met the objectives outlined above and brought together in a decision-making framework the work to date in the field. Since then, the model has been subject to extensive revisions and expansion of its capabilities, particularly in the areas of estimation of road surface deterioration and the impact of design standards and surface conditions on road user costs, as new information has become available (e.g., 80, 81), culminating in the most recent version (56) of the model which is now being tested and used in Ethiopia. Somewhat parallel and complementary to M.I.T.'s efforts have been those of the Transport and Road Research Laboratory (TRRL) which, largely on the basis of field work carried out in Kenya in the seventies, produced their own road transport investment model for developing countries (82).

It is the HCM which is used in the study at hand because it integrates many of the existing methodologies of evaluating alternative designs in terms of the three costs; it is also operational, computerized, and readily available with personnel at M.I.T. knowledgeable about and willing to assist in its use. As the HCM is representative of this class of models, it seems appropriate to make a few comments about its basic

framework and more pertinent features.

Project-level engineering decisions, such as choice of alignment, geometric standards, surface type, maintenance policy, and construction and maintenance methods, and their implications for total transport costs are the focus of the model. The basic function of the HCM, estimating construction, maintenance, and user costs for a road, is done by simulating the life of the road, beginning with its initial construction and proceeding through periodic upgrading as well as the yearly cycle of use, deterioration, and maintenance. On a year-by-year basis throughout the analysis period then, construction and maintenance activities to be performed are determined, and road conditions, traffic volumes, and all associated costs are estimated; Figure 2.4 gives the basic structure of the model. The output of the simulation includes a yearly accounting of construction, maintenance, and user costs as well as a detailed history of the status and deterioration of the road. Construction and maintenance costs can be broken down into their components of labor, equipment, materials, and overhead and profit, while user costs can be disaggregated to the vehicle operating costs for each type of vehicle using the road. It might additionally be noted that all estimates in the course of the simulation are made in terms of physical quantities, from which total costs are obtained by applying the appropriate unit rates, allowing the use of any monetary system. Moreover, construction and maintenance technology are inherently expressed in the unit costs input to the model, while transport technology is inherent in the vehicle characteristics

Figure 2.4: Basic structure of the HCM (source: ref. 56).

DATA REQUIREMENTS

National or Regional Parameters

- Design Standards
  - Geometric standards
  - Pavement sections
  - Material characteristics
- Maintenance Standards
  - Routine maintenance criteria for earth, gravel, and paved roads
  - Resurfacing criteria

Highway Program Parameters

- Construction Unit Costs
- Maintenance Unit Costs
- Basic Vehicle Characteristics and Ownership and Operating Costs

Project Parameters

- Traffic
- Physical Characteristics of the Alignment
- Specific Design and Maintenance Standards to Be Studied
- Schedule for Implementation

SIMULATION OF ROAD LIFE CYCLE

For each year in analysis period

↓

Estimate costs for road construction or upgrading based on physical characteristics of the alignment, design standards, and construction unit costs

↓

Update the status of the road based on project completions

↓

Preliminarily estimate this year's traffic based on that of past year and expected growth

↓

Estimate road deterioration as a function of design standards, past year's surface conditions, traffic, and environment; effects of maintenance and their costs; and average surface conditions

↓

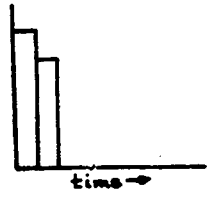
Estimate user costs based on geometric standards and surface type and condition

↓

Update traffic projections based on actual user costs

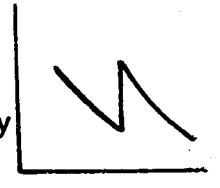
RESULTS

Construction Costs

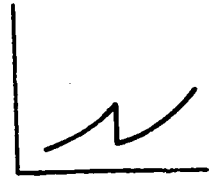


Maintenance Costs

Surface Conditions (present serviceability index)



User Costs ($/vehicle/kilometer)



and costs input, and thus all can be varied.

2.3 Method of Approach Used in Research

The analysis of technology and its change in highway construction in the U.S. in the research at hand follows a micro-study approach patterned after the case studies reviewed in Section 2.21. In an effort to also consider the interaction of design and technology in highway construction and use, the current study goes somewhat beyond these earlier ones in implementing one of the models of Section 2.22 for evaluating total project costs. Moreover, certain of the economic concepts and tools discussed in Section 2.1 are used in the analysis of the results.

The basic analytic procedure thus entails first observing and recording the inputs required for and influences impacting the various tasks of production, for alternative means of producing a given output; this data is then used to synthesize a production isoquant for the good which is subjected to further economic analysis. Since it is obviously impossible to actually observe the technologies of the past in the field today, historical data used in a simulation framework must suffice; thus, the various stages of highway construction and complete road projects can be hypothetically built and operated, by means of alternative technical packages and project designs. This is accomplished in two levels of analysis: (1) the stage-level, where each of the various stages of construction constitutes an output, with the labor, capital, and materials of the various technical packages for each stage being the inputs; and (2) the

project-level, where a road project capable of handling a particular volume of traffic constitutes the output, with the construction, maintenance, and user costs of the alternative projects designed for the particular traffic being the inputs, although these are also considered in a more disaggregate sense as, for example, the labor, capital, and materials requirements of the construction phase. Each level of analysis is discussed in turn below.

2.31 Stage-Level Analysis

The basic data required for the stage-level analysis consists of the alternative technical packages, available at various points in time in the U.S., for the various stages of road construction, and the resource productivities and costs of these packages under typical environmental and institutional conditions. The productivities of the various resources included in each technical package are generally available at the activity or task level and are thus aggregated to the stage level. At this point, the unit prices of the resources can be applied, for example, to arrive at the unit costs of the various technical packages of each stage of construction. For each technical package for each stage of construction, where output is measured in physical units of a given rate of production (e.g., 100 bank cubic meters per hour) or units produced (e.g., 100 bank cubic meters), the following set of results is generated for further analysis: (1) skilled and unskilled labor input, separately or in combination, expressed in physical units of men or man-hours or in cost terms; (2) equipment input measured in value terms of investment, straight-line depreciation

(thus introducing life), or total ownership and operating cost (or its various components of capital recovery, maintenance and miscellaneous, and fuel and lubrication costs); (3) animal (horse) input expressed in value terms along the lines of those of equipment; (4) materials input measured in cost terms; and (5) total unit cost, including all resources involved. This is done for each of three technology periods under various pricing conditions. Section 3.1 and Appendix B provide further details on the collection and preliminary analysis of data for the stage-level analysis.

Given these results then, the analysis of technology change in highway construction over time in the U.S. is basically a three step process: (1) a qualitative investigation of how the technical packages, in terms of the resources constituting them, have changed; (2) an efficiency analysis, whereby graphical and numerical techniques are used in narrowing the production set to those technical packages which are efficient, for each stage of construction, for each technology period and over all periods; and (3) an analysis narrowing the efficient set of technical packages for each technology period and over all periods to those which are best-practice at prices representative of each of the three technology periods, such that technology change and its characteristics can be identified and quantified.

The qualitative analysis concerning changes in the nature of the technical packages requires, for each stage of construction for each technology period, a listing of the technical packages and the resources constituting them, as well as a graphical representation of the resource

requirements of each package. The graphs used in the graphical efficiency analysis, discussed next, can fulfill any need for analytic tools at this step.

Narrowing the full set of technical packages to those which produce the most output for the least input can be accomplished by means of graphical or numerical analytic techniques; both are used in the case at hand. The graphical approach basically entails plotting the labor and capital requirements of the various technical packages for each period for a given rate or level of production, potentially yielding production isoquants. Certain difficulties are encountered in this approach, including the omission of other resources required for production, such as materials, although they could be included as additional dimensions, and selection of the units of measurement of the resources, some possible measures of capital, for example, being investment, hourly depreciation, or hourly ownership and operating costs at various possible base periods. Discussion and testing of alternative solutions to these difficulties for the case at hand is covered in Section 4.11. The outcome is that omission of resources other than labor and capital is justified; labor is reasonably measured in terms of unskilled men, where the skilled input is weighted by the skilled/unskilled wage ratio at the time of the technology, before being added to the unskilled input, while capital is most suitably measured in 1974 (i.e., current) investment dollars.

A numerical efficiency analysis is used as a back-up to the graphical approach, whereby the engineering variables are held constant while the

economic ones are allowed to vary over a wide range; efficient technical packages are defined as those which are least-cost under at least one set of reasonable economic conditions. The following equation is used throughout the study to estimate the total unit costs of the technical packages:

$$\text{UNITCOST} = \overbrace{(\text{skcost} \cdot \text{SKREQ} + \text{unskcost} \cdot \text{UNSKREQ})}^{\text{labor costs}} +$$

$$\overbrace{\sum_k \left\{ \left\{ P_{kt} \left[\frac{\text{index}}{\text{INDEX}_t} \right] \left[\frac{\frac{(1+i)^{N_k} i}{(1+i)^{N_k} - 1}}{H_k} + \frac{\text{MAINT}_k}{N_k H_k} + .055 \frac{(N_k + 1)}{2 N_k H_k} \right] + 1.35\,(\text{ccost} \cdot \text{CREQ}_k + \text{gcost} \cdot \text{GREQ}_k + \text{dcost} \cdot \text{DREQ}_k) \right\} \cdot \text{EQREQ}_k \right\}}^{\text{equipment costs}} +$$

$$\overbrace{(\text{hcost} \cdot \text{HREQ})}^{\text{horse costs}} + \overbrace{\sum_j (\text{mcost}_j \cdot \text{MREQ}_j)}^{\text{material costs}}$$

where small letters indicate economic variables

capital letters indicate engineering variables

subscript k = item of equipment

subscript t = year of equipment investment cost

subscript j = material

___cost = hourly or per unit quantity cost of the resource, with sk = skilled labor, unsk = unskilled labor, c = coal, g = gasoline, d = diesel fuel, h = horse, m = material*

___REQ = hours or quantity of the resource required per unit of output (exceptions: $CREQ_k$, $GREQ_k$, $DREQ_k$ = quantity of fuel consumed per hour by equipment k), with prefixes as for ___cost adding EQ = equipment

P_{kt} = investment cost of equipment k in year t

index = index used to inflate or deflate equipment investment cost in line with particular economic conditions being considered

$INDEX_t$ = equipment investment cost index in year t

i = interest rate

N_k = life in years of equipment k

H_k = annual hours of utilization of equipment k

$MAINT_k$ = maintenance over life as a percentage of investment cost of equipment k

---

*Generally only site preparation materials are included, as those for surfacing are the same across all technical packages for one surface type.

The economic variables are divided into four groups, labor (skilled and unskilled), interest rate, equipment (index, equipment consumables, and materials assisting in construction), and horse, and various sets of economic conditions (e.g., the U.S. in 1974) are defined. The economic conditions of the four resource groups are allowed to vary independently of one another, and the unit costs of the full set of technical packages are calculated for each combination of economic conditions; thus the technical packages which arise as least-cost under at least one reasonable combination of economic conditions can be identified. The result, for each stage, for each technology period and over all periods, is the set of efficient technical packages, which can be compared to the respective result of the graphical analysis. The primary shortcoming of this analytic technique is that the range of combinations of economic conditions encountered in the analysis may not be fully representative of those in existence, and the results may, therefore, not be all-inclusive. Given the two analytic techniques, however, it seems a reasonably reliable picture of the set of efficient technical packages should be obtainable.

In beginning to address the issue of efficiency and substitution and their role in technology change, it was decided to pursue an approach either (1) along the lines of Salter (73), who tries to divide the change in factor productivity into its component parts; or (2) along the lines of the theoretical production functions, such as the Cobb-Douglas and CES, whereby the characteristics of a technology can be expressed by various combinations of the empirically determined parameters of the function.

Both approaches are discussed in Section 2.1 along with their various shortcomings. The results of the efficiency analysis, however, pretty much preclude the use of theoretical production functions. Production functions were found to exist for the various stages of construction for only the first of three technology periods identified in the course of the analysis and for the overall case. Furthermore, in the two cases where production functions do exist, the measurement of capital is a problem; investment cost is the standardly accepted measure in the economic literature, but it does not seem so appropriate here due to the wide variation in the lifetime, maintenance as a percentage of investment, and fuel consumption exhibited by the items of equipment included in the efficient set. An approach along the lines of Salter's seems somewhat more viable and is thus the one pursued in the study at hand.

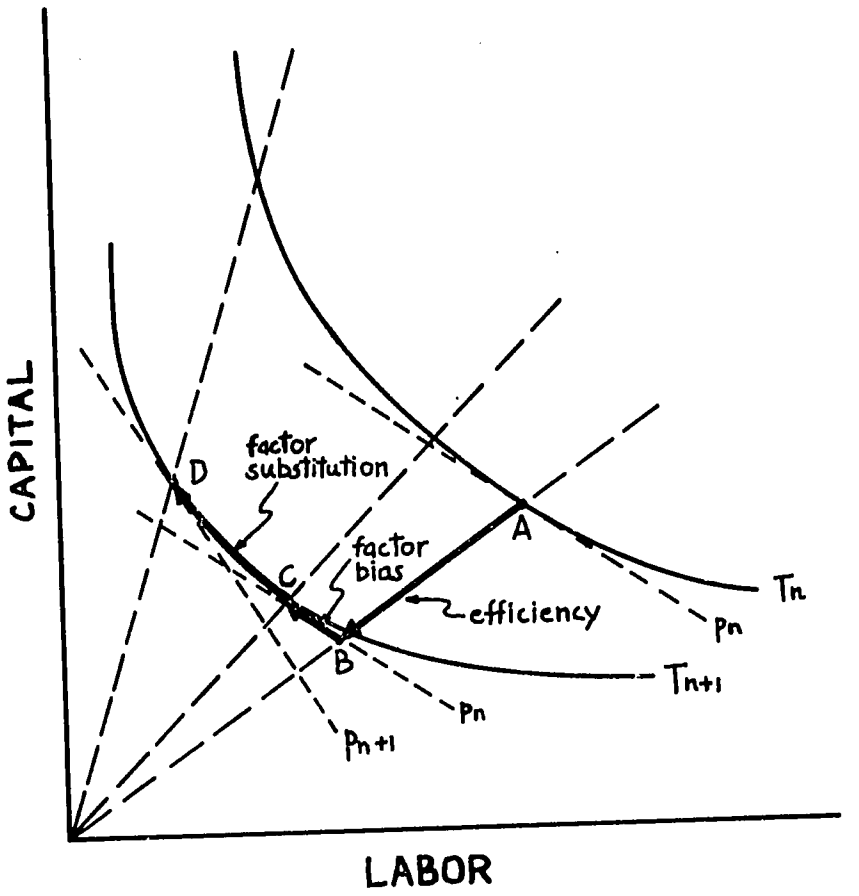
Salter views technology change as represented by movements over time of the best-practice techniques. The first step, therefore, consists of narrowing the set of technical packages for each technology period to those which are least-cost, and thus best-practice, at prices representative of each of the three technology periods. The full set of technical packages for each stage of construction is costed by means of the unit cost equation given above, and the least-cost packages are identified as well as any others that are within 10 percent in cost; these, then, make up the least-cost set.

Having thus reduced the set of technical packages to the best-practice ones, it is useful to return to a graphical approach to observe the

magnitude of the technology change that has occurred over the years in terms of overall costs and factor inputs. For example, it is of interest to see the progression of the unit costs of each stage of construction over time, both as they actually occurred and as they would have occurred had technology not changed as it did. Coincidently, as suggested by Carter (15), and in line with Salter's analysis, it is useful to observe the change over time in the quantities of various resources required to produce a certain rate or level of output. After testing alternative measures in Section 4.12, it is decided to use unskilled men and 1974 investment costs, as in the graphical efficiency analysis; this is perhaps more appropriate here, as the equipment of the earlier best-practice packages is somewhat more in line with that of later packages than is generally the case. For each stage of construction, then, the labor and capital requirements of the best-practice packages of each technology period are looked at as a percentage of those of previous technology periods.

Given this quantitative measure of technology change then, by means of Salter's approach, it is possible to begin to divide it into its component parts. Figure 2.5 is useful as a first step in that it depicts the disaggregation of the movement of best-practice packages over time into its component parts. It should be noted that in this study, as in Salter's analysis, returns to scale are assumed constant, leaving efficiency, factor bias, and factor substitution as the characteristics of technology change. As indicated by Figure 2.5, factor substitution occurs with changes in relative factor prices. In the course of deriving

Figure 2.5: Schematic representation of dividing technology change, represented by movements over time of best-practice techniques, into its component parts.



Note: Constant returns to scale are assumed.

A = best-practice technical package at the prices of period n, given T_n as the production isoquant.

B = theoretical technical package defined to separate the effects of efficiency and bias; its capital/labor ratio is the same as that of A, while its cost is the same as that of C.

C = best-practice technical package at the prices of period n, given T_{n+1} as the production isoquant, or both T_n and T_{n+1}.

D = best-practice technical package at the prices of period n + 1, given T_{n+1} as the production isoquant, or both T_n and T_{n+1}.

the set of best-practice packages for each technology period and over all periods at prices representative of each of the three technology periods, however, it was discovered that, with but a few minor exceptions, the best-practice packages for each stage of construction in each technology period are the same for all three price periods (i.e., points C and D are the same in Figure 2.5); moreover, the best-practice packages of each technology period exhibit lower costs than those of previous periods for all three price periods (i.e., point C is lower in cost than is point A in Figure 2.5). The first finding suggests that substitution, brought about by changes in factor prices over the period covered by the technologies being studied, has not played a significant role in the technology change observed over that period; the second suggests that efficiency has had some part. This approach is similar to one used by Buechner (14) in determining whether observed occupational changes were the result of technological or technical change.

What remains in the study at hand, then, is the separation of the roles of efficiency and factor bias; such is depicted in Figure 2.5. Based on Salter's work and after some testing of alternative pricing schemes as discussed in Section 4.12, the following generic form of the equation for estimating the fractional change in unit resource requirements accounted for by efficiency was selected:

$$\frac{L_B - L_A}{L_A}, \quad \frac{K_B - K_A}{K_A} = \frac{w_n L_C + g_n K_C}{w_n L_A + g_n K_A} - 1$$

where subscripts A, B, C refer to points on Figure 2.5

subscript n = initial period

L = labor in men required for a given rate of production

K = capital in investment dollars required for a given rate of production; any price period may be used on the left side of the equation, but period n must be used on the right side

w_n = hourly wage rate in period n

g_n = hourly capital recovery factor in period n

This measure of efficiency can readily be derived by simultaneously solving two equations defining point B in Figure 2.5, one stating the equality of the capital/labor ratios at points A and B and the other stating the cost equality of points B and C. In the case at hand, a uniform wage rate and capital recovery factor do not exist, and thus each item of labor (i.e., skilled and unskilled) and equipment (i.e., varying in terms of lifetime) is priced at its own wage rate or capital recovery factor before summing on the right-hand side of the above equation; L and K on the left-hand side are respectively measured in unskilled men and 1974 investment costs.

Salter also develops an equation for estimating the fractional change in unit resource requirements accounted for by bias as follows:

$$\frac{L_C - L_B}{L_A} = -\pi_n \left(\frac{K_C/L_C}{K_A/L_A} - 1 \right)$$

$$\frac{K_C - K_B}{K_A} = (1 - \pi_n) \left(\frac{K_C/L_C}{K_A/L_A} - 1 \right)$$

where π_n = share of capital costs in total costs in period n; in the case at hand, it is interpreted as the average for the packages (i.e., points A and C) being compared

Salter's measure of bias, however, is but an indication of the direction and potential magnitude of bias' influence on resource quantities and not really a true measure. In this study, the specific resource requirements of points A and C are known, and thus bias' part in the fractional change in unit resource requirements is simply as follows:

$$\frac{L_C - L_B}{L_A} = \underbrace{\frac{L_C - L_A}{L_A}}_{\text{total fractional change}} - \underbrace{\frac{L_B - L_A}{L_A}}_{\text{efficiency's share}}$$

$$\frac{K_C - K_B}{K_A} = \frac{K_C - K_A}{K_A} - \frac{K_B - K_A}{K_A}$$

With these analytic tools, then, the relative roles of efficiency, bias, and substitution in technology change over time, as well as the magnitude of technology change itself, can be identified and quantified for the various stages of road construction in the U.S.

2.32 Project-Level Analysis

Variations in project designs and/or construction procedures can potentially lead to trade-offs among the various stages of construction and/or between the construction and operation phases of a highway project, and can thus be investigated only at the level of the complete project. Such interaction of design and technology in highway construction and use makes it important to extend the stage-level analysis to the project-level. In an effort to begin to investigate some of these issues, this research looks at alternative surfacing materials, various subgrade strength/surface design combinations, and alternative scenarios for obtaining fill materials, for a couple of design standards and traffic volumes.

The data required for the project-level analysis consists of the construction quantities and the efficient technical packages (and thus resource requirements and unit costs from the stage-level analysis) for each technology period and over all periods, for the various stages of construction of a representative set of alternative projects; also needed are the maintenance and user costs associated with these projects at various price periods. Although it seemed desirable at the outset to use designs commensurate with each technology period, this proved to be somewhat infeasible due to a paucity of early design information; it was decided instead to design projects at the low and high end of the spectrum for today's two-lane, low volume, rural roads for two different traffic volumes. The production function based aggregation procedure, as performed in the IBRD-I (42) and ILO-Iran (44) studies discussed in Section 2.21, seemed to present a suitable means by which to aggregate the various stages of construction, with their respective quantities and sets of efficient technical packages, for each technology period and over all periods, to the alternative projects. The findings of the stage-level analysis given above, however, indicate that, over the range of prices representative of the three technology periods, there is effectively no choice of technology, and thus no need for such an aggregation procedure. It was therefore decided to do the project-level analysis at prices representative of the U.S. over this period, simply using the best-practice technical packages identified in the stage-level analysis. Since production functions do exist in two cases, however, it was decided to also use a more extreme set of pricing conditions (e.g., those of a

developing country), such that some of the alternative technical packages in these cases might appear in the least-cost set and be used in the project-level analysis as well.

For each project, under various technology and price conditions, where output is measured in terms of the volume of traffic the project is designed to carry over its life, the following results are generated for further analysis: (1) total, and per unit traffic, construction costs and its various components of labor, capital, materials, and overhead and profit, among other subtotals; (2) total, and per unit traffic, maintenance costs over the life of the project, both expressed in net present value terms and the former in equivalent annual cost terms as well; (3) total, and per unit traffic, user costs over the life of the project, similarly expressed; and (4) total, and per unit traffic, project costs over the life of the project, expressed in net present value terms. Section 3.2 and Appendix C provide further details on the collection and preliminary analysis of data for the project-level analysis.

The first step in the project-level analysis is a graphical efficiency analysis, patterned after one proposed by Soberman (76), investigating the trade-offs between current and future expenditures in highway construction and use resulting from the design and technology mix. For each project and each technology period and over all periods, the maintenance and user costs incurred over the life of the project, expressed in terms of equivalent annual costs, are plotted against the construction costs. As these are value rather than quantity-based measures, it is appropriate to do this for a couple of price conditions representative

of the U.S. over the period of the technologies observed. In order to broaden the analysis and test the sensitivity of the results to economic conditions, and as there is some choice of technology in the case of one technology period and the overall case, a more extreme set of prices, like those of a developing country today, are also used.

Given the various sets of efficient projects for each project group, under various price and technology conditions, it is next useful to narrow these to those projects which are least-cost in terms of total project costs, expressed as equivalent annual or net present values. Little distinction is found, however, among project alternatives and even among alternative technologies in the various project groups at the level of total project costs. A similar analysis with these costs disaggregated into partial construction (predominantly labor and capital), total construction, maintenance, and user cost components is thus necessary, in order to see the dominance of various cost factors and to see where differences among the projects and technologies lie. A graphical presentation of these cost components (and, in turn, their components) for a couple of projects, for each technology period, at prices representative of the U.S. over this period, serves as a useful tool. It provides some insight into the relative magnitudes of these various cost components as well as their change over time in the U.S., and, most importantly, it indicates the magnitude of the cost-reducing influence of technology change in highway construction at the project level. At the same time, it should be noted that materials usage, maintenance policies and procedures, and transport technology are assumed constant at about the level of today.

CHAPTER 3

DATA COLLECTION AND ANALYSIS

The primary aim of this chapter is the presentation of the results of the two-level analysis of data, one section being devoted to the stage and one to the project-level analysis. Each of the sections begins with some largely definitional comments pertaining to the level of analysis, followed by a brief description of the actual collection and analysis of the basic data such as the nature and scope of the data base and some of the problems encountered and solutions arrived at in its use. The presentation of the results, the detailed discussion of which is left to Chapter 4, finally completes each section. More detailed discussion of the data collection and preliminary analysis procedures, as well as presentation of the basic data and its sources and of some of the results, can be found in Appendices B and C.

3.1 Construction Technologies and Costs

The construction procedure for highways may be divided into various stages: site preparation, earthwork, subbase, base, and surfacing, minor structures, and major structures. Each stage, in turn, is made up of several activities; earthwork, for example, consists of excavate, load, haul, unload, return, spread, and compact and finish. Similarly, tasks can be defined as groups of possibly interdependent activities such as the earthwork activities, excavate through return. The resources used include various types of labor, equipment, and materials.

Some of the environmental conditions which might be of importance on a project are climate, vegetation, terrain, soil/rock type, lift height, and haul distance and condition; similarly, some of the institutional conditions are management and organization, physical condition and skill of the workers, method of payment, social welfare of the workers, and availability and quality of the maintenance and repair facilities. The data required for the study at hand thus consists of the alternative technical packages, available at various points in time in the U.S., for the various stages of road construction, and the resource productivities and costs of these packages under typical environmental and institutional conditions.

3.11 Identification of Technical Packages

For the purposes of this study, the stages of construction are somewhat rearranged, on the basis of their activities, into site preparation, excavation/hauling (with subgroups for haul distance), spreading/compaction (with subgroups for degree of compaction), and surfacing (with subgroups for the material, assuming a constant degree of compaction). It was decided at the outset to eliminate major structures from the analysis, as they are rather distinct and separate from the other stages of construction, and merit a study of their own. Minor structures are also not included, due to the scarcity of data in this area and to their relatively small contribution to highway construction costs. It should be noted, however, that these two stages are often relatively labor-intensive, have considerable potential for labor-capital substitution, and might even be used in place of certain parts of other stages

(e.g., using a bridge instead of a large fill, or a retaining wall to lessen the amount of cut necessary).

In identifying the technical packages for the various stages of road construction, three time periods evolve quite naturally: (1) the 1920's, primarily representing those methods in use around 1915 to 1937; (2) the 1950's, representing those around 1945 to 1962; and (3) the 1970's, representing those around 1965 to 1975. These time periods coincide, by and large, with those during which the U.S. Federal Highway Administration (FHWA) carried out their production studies of alternative highway construction methods, these being about 1920-37, 1945-66, and 1971-present; the results of these studies are compiled in various unpublished forms (e.g., 97, 98), as summary articles in Public Roads (e.g., 2, 32, 33), and, for the current studies, as reports available through the National Technical Information Service (e.g., 105). The sources used in identifying alternative technical packages are the same as those used in estimating resource productivities for these packages, including the FHWA studies mentioned above as well as various methods and costs, cost estimating, and engineering books and handbooks (e.g., 29, 46, 67, 77) among other publications of the period.

The set of technical packages identified for each period for each stage of construction is given in Table 3.1, where the various resources constituting each package are specified, the equipment being organized by the major activities or tasks the stage involves. As a convenient means of referring to the various packages, a numbering scheme has been devised. The digits represent the major activities or tasks of the

Table 3.1a: Technical packages for site preparation in the 1920's, 1950's, and 1970's.

Period and No. of Technical Package	Labor	Equipment: Brush and Tree Removal	Equipment: Burning Debris	Materials
1920: 11	Skilled Unskilled	Handtools (201) Horse	Handtools (201)	Dynamite (820) Fuse (821) Caps (822)
21	Skilled Unskilled	80 hp tractor (630) Bulldozer blade (602)	Handtools (201)	
1950: 11	Skilled Unskilled	Chain saw (235) Handtools (207,208)	Handtools (206)	Dynamite (820) Fuse (821) Caps (822)
21	Skilled Unskilled	90 dbhp tractor (642) Bulldozer blade (608)	Handtools (206)	
31	Skilled Unskilled	90 dbhp tractor (642) Bulldozer blade (608) Cable (610)	Handtools (206)	
1970: 11	Skilled Unskilled	Chain saw (236) Brush saw (241) Backhoe (237) Handtools (209)	Handtools (209)	Kerosene (823)
21	Skilled Unskilled	70 dbhp tractor (644) Bulldozer blade (614) Chain saw (236) Pickup truck (336) Handtools (209)	Handtools (209)	Kerosene (823)
31	Skilled Unskilled	180 fwhp tractor (645) Bulldozer blade (615)	Handtools (209)	Kerosene (823)

Table 3.1b: Technical packages for excavation/hauling in the 1920's, 1950's, and 1970's.

Period and No. of Technical Package	Labor	Equipment: Excavation	Equipment: Hauling
1920: 1-1	Skilled Unskilled	Handtools (202)	Wheelbarrow (301)
1-2	Skilled Unskilled	Handtools (202)	Handcart (302)
2-1	Skilled Unskilled	Plow (203) Horse Handtools (202)	Wheelbarrow (301)
2-2	Skilled Unskilled	Plow (203) Horse Handtools (202)	Handcart (302)
3-1	Skilled Unskilled	Plow (203) 20 hp tractor (631) Handtools (202)	Wheelbarrow (301)
3-2	Skilled Unskilled	Plow (203) 20 hp tractor (631) Handtools (202)	Handcart (302)
4-3	Skilled Unskilled	Dragscraper (604) Plow (203) Horse	Dragscraper (604) Horse
5-4	Skilled Unskilled	Fresno (603) Plow (203) Horse	Fresno (603) Horse

Table 3.1b: Technical packages for excavation/hauling in the 1920's 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Excavation	Equipment: Hauling
1920: 6-5	Skilled Unskilled	Wheelscraper (605) Plow (203) Horse	Wheelscraper (605) Horse
7-6	Skilled	60 hp tractor (633) Bulldozer blade (606)	60 hp tractor (633) Bulldozer blade (606)
8-7	Skilled Unskilled	Elevating grader (205) Horse Handtools (202)	1.5 cy wagon (303) Horse
9-7	Skilled Unskilled	Elevating grader (205) 30 hp tractor (634) Handtools (202)	1.5 cy wagon (303) Horse
10-7	Skilled Unskilled	Power shovel (230) 3/4 cy shovel dipper (204) Handtools (202)	1.5 cy wagon (303) Horse
10-8	Skilled Unskilled	Power shovel (230) 3/4 cy shovel dipper (204) Handtools (202)	5 cy wagon (304) 20 hp tractor (631)
10-9	Skilled Unskilled	Power shovel (230) 3/4 cy shovel dipper (204) Handtools (202)	3.5 ton truck (330)
1950: 1-1	Skilled	1.5 cy power shovel (231)	10 ton truck (332)
1-2	Skilled	1.5 cy power shovel (231)	20 ton truck (333)

Table 3.1b: Technical packages for excavation/hauling in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package		Labor	Equipment: Excavation	Equipment: Hauling
1950:	1-3	Skilled	1.5 cy power shovel (231)	8.5 cy wagon (305) 125 fwhp tractor (638)
	1-4	Skilled	1.5 cy power shovel (231)	15 cy wagon (306) 185 fwhp tractor (639)
	2-1	Skilled	2.0 cy power shovel (232)	10 ton truck (332)
	2-2	Skilled	2.0 cy power shovel (232)	20 ton truck (333)
	2-3	Skilled	2.0 cy power shovel (232)	8.5 cy wagon (305) 125 fwhp tractor (638)
	2-4	Skilled	2.0 cy power shovel (232)	15 cy wagon (306) 185 fwhp tractor (639)
	3-1	Skilled	2.5 cy power shovel (233)	10 ton truck (332)
	3-2	Skilled	2.5 cy power shovel (233)	20 ton truck (333)
	3-3	Skilled	2.5 cy power shovel (233)	8.5 cy wagon (305) 125 fwhp tractor (638)
	3-4	Skilled	2.5 cy power shovel (233)	15 cy wagon (306) 185 fwhp tractor (639)
	4-2	Skilled	Elevating grader (234) 90 dbhp tractor (642)	20 ton truck (333)
	4-4	Skilled	Elevating grader (234) 90 dbhp tractor (642)	15 cy wagon (306) 185 fwhp tractor (639)

Table 3.1b: Technical packages for excavation/hauling in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Excavation	Equipment: Hauling
1950: 5-5	Skilled	6 cy scraper (611) 125 fwhp wheel tractor (638) 70 hp crawler tractor (641) 8 ft bulldozer blade (607)	6 cy scraper (611) 125 fwhp wheel tractor (638)
6-6	Skilled	9 cy scraper (612) 185 fwhp wheel tractor (639) 90 hp crawler tractor (642) 10 ft bulldozer blade (608)	9 cy scraper (612) 185 fwhp wheel tractor (639)
7-7	Skilled	15 cy scraper (613) 250 fwhp wheel tractor (640) 130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	15 cy scraper (613) 250 fwhp wheel tractor (640)
8-8	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	70 hp crawler tractor (641) 8 ft bulldozer blade (607)
9-9	Skilled	90 hp crawler tractor (642) 10 ft bulldozer blade (608)	90 hp crawler tractor (642) 10 ft bulldozer blade (608)
10-10	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)
11-0	Skilled	Blade grader (423)	
1970: 1-1	Skilled	1.5 cy power shovel (238)	10 ton truck (337)
1-2	Skilled	1.5 cy power shovel (238)	15 ton truck (338)
2-3	Skilled	2.5 cy power shovel (239)	20 ton truck (339)

Table 3.1b: Technical packages for excavation/hauling in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Excavation	Equipment: Hauling
1970: 2-5	Skilled	2.5 cy power shovel (239)	15 cy wagon and tractor (341)
3-4	Skilled	3.5 cy power shovel (240)	35 ton truck (340)
3-6	Skilled	3.5 cy power shovel (240)	27 cy wagon and tractor (342)
4-1	Skilled	1.75 cy front end loader (646)	10 ton truck (337)
4-2	Skilled	1.75 cy front end loader (646)	15 ton truck (338)
4-7	Skilled	1.75 cy front end loader (646)	1.75 cy front end loader (646)
5-3	Skilled	3.0 cy front end loader (647)	20 ton truck (339)
5-5	Skilled	3.0 cy front end loader (647)	15 cy wagon and tractor (341)
5-8	Skilled	3.0 cy front end loader (647)	3.0 cy front end loader (647)
6-4	Skilled	5.0 cy front end loader (648)	35 ton truck (340)
6-6	Skilled	5.0 cy front end loader (648)	27 cy wagon and tractor (342)
6-9	Skilled	5.0 cy front end loader (648)	5.0 cy front end loader (648)
7-10	Skilled	11.5 cy elevating scraper (649)	11.5 cy elevating scraper (649)
8-11	Skilled	21.5 cy elevating scraper (650)	21.5 cy elevating scraper (650)
9-12	Skilled	20 cy scraper (651) 270 hp crawler tractor (653) 12 ft bulldozer blade (616)	20 cy scraper (651)

Table 3.1b: Technical packages for excavation/hauling in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Excavation	Equipment: Hauling
1970: 10-13	Skilled	30 cy scraper (652) 385 hp crawler tractor (654) 14 ft bulldozer blade (617)	30 cy scraper (652)
11-14	Skilled	70 hp crawler tractor (644) 8 ft bulldozer blade (614)	70 hp crawler tractor (644) 8 ft bulldozer blade (614)
12-15	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	180 hp crawler tractor (645) 12 ft bulldozer blade (616)
13-16	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	385 hp crawler tractor (654) 14 ft bulldozer blade (617)
14-0	Skilled	Motor grader (424)	

Note: Technical package 11-0 in 1950 and 14-0 in 1970 are for simply excavating a small ditch alongside a road; in the 1920's this would be done with any package up to and including 6-5.

Table 3.1c: Technical packages for spreading/compaction in the 1920's, 1950's, and 1970's.

Period and No. of Technical Package	Labor	Equipment: Spreading	Equipment: Compaction
1920: 11	Skilled Unskilled	Handtools (401)	2.5 ton roller (501) Horse
21	Skilled Unskilled	7 ft blade grader (402) Horse	2.5 ton roller (501) Horse
12	Skilled Unskilled	Handtools (401)	6 ton roller (530)
22	Skilled Unskilled	7 ft blade grader (402) Horse	6 ton roller (530)
32	Skilled	12 ft blade grader (403) 76 hp tractor (632)	6 ton roller (530)
1950: 11	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	Sheepsfoot roller (502) 70 hp crawler tractor (641)
12	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	Sheepsfoot roller (502) 90 hp crawler tractor (642)
13	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	3 wheel roller (532)
14	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	Pneumatic roller (533)

Table 3.1c: Technical packages for spreading/compaction in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Spreading	Equipment: Compaction
1950: 21	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	Sheepsfoot roller (502) 70 hp crawler tractor (641)
22	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	Sheepsfoot roller (502) 90 hp crawler tractor (642)
23	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	3 wheel roller (532)
24	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	Pneumatic roller (533)
31	Skilled	10 ft blade grader (420)	Sheepsfoot roller (502) 70 hp crawler tractor (641)
32	Skilled	10 ft blade grader (420)	Sheepsfoot roller (502) 90 hp crawler tractor (642)
33	Skilled	10 ft blade grader (420)	3 wheel roller (532)
34	Skilled	10 ft blade grader (420)	Pneumatic roller (533)
41	Skilled	13 ft blade grader (421)	Sheepsfoot roller (502) 70 hp crawler tractor (641)
42	Skilled	13 ft blade grader (421)	Sheepsfoot roller (502) 90 hp crawler tractor (642)
43	Skilled	13 ft blade grader (421)	3 wheel roller (532)
44	Skilled	13 ft blade grader (421)	Pneumatic roller (533)

Table 3.1c: Technical packages for spreading/compaction in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Spreading	Equipment: Compaction
1970: 11	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Sheepsfoot roller (536)
12	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Sheepsfoot roller (503) 270 hp crawler tractor (653)
13	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Pneumatic roller (537)
14	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Vibratory roller (538)
21	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Sheepsfoot roller (536)
22	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Sheepsfoot roller (503) 270 hp crawler tractor (653)
23	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Pneumatic roller (537)
24	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Vibratory roller (538)
31	Skilled	12 ft motor grader (425)	Sheepsfoot roller (536)
32	Skilled	12 ft motor grader (425)	Sheepsfoot roller (503) 270 hp crawler tractor (653)
33	Skilled	12 ft motor grader (425)	Pneumatic roller (537)
34	Skilled	12 ft motor grader (425)	Vibratory roller (538)

Table 3.1c: Technical packages for spreading/compaction in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package		Labor	Equipment: Spreading	Equipment: Compaction
1970:	41	Skilled	14 ft motor grader (426)	Sheepsfoot roller (536)
	42	Skilled	14 ft motor grader (426)	Sheepsfoot roller (503) 270 hp crawler tractor (653)
	43	Skilled	14 ft motor grader (426)	Pneumatic roller (537)
	44	Skilled	14 ft motor grader (426)	Vibratory roller (538)

Note: Technical packages 11, 21, 31 and 41 in 1950 use two 4 ft wide rollers pulled by a tractor, while technical packages 12, 22, 32, and 42 in 1950 use four such rollers and a larger tractor.

Table 3.1d: Technical packages for gravel surfacing in the 1920's, 1950's, and 1970's.

Period and No. of Technical Package		Labor	Equipment: Spreading Gravel	Equipment: Compacting Gravel
1920:	11	Skilled Unskilled	Handtools (401)	2.5 ton roller (501) Horse
	21	Skilled Unskilled	5 ft blade grader (404) Horse Handtools (401)	2.5 ton roller (501) Horse
	12	Skilled Unskilled	Handtools (401)	6 ton roller (530)
	22	Skilled Unskilled	5 ft blade grader (404) Horse Handtools (401)	6 ton roller (530)
1950:	11	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	3 wheel roller (534)
	12	Skilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	Pneumatic roller (533)
	21	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	3 wheel roller (534)
	22	Skilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	Pneumatic roller (533)
	31	Skilled	10 ft blade grader (420)	3 wheel roller (534)
	32	Skilled	10 ft blade grader (420)	Pneumatic roller (533)
	41	Skilled	13 ft blade grader (421)	3 wheel roller (534)

Table 3.1d: Technical packages for gravel surfacing in the 1920's, 1950's and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Spreading Gravel	Equipment: Compacting Gravel
1950: 42	Skilled	13 ft blade grader (421)	Pneumatic roller (533)
51	Skilled Unskilled	Gas spreader (422) 20 ton truck (333) Handtools (408)	3 wheel roller (534)
52	Skilled Unskilled	Gas spreader (422) 20 ton truck (333) Handtools (408)	Pneumatic roller (533)
1970: 11	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	3 wheel roller (539)
12	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Pneumatic roller (537)
13	Skilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Vibratory roller (538)
21	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	3 wheel roller (539)
22	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Pneumatic roller (537)
23	Skilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Vibratory roller (538)
31	Skilled	12 ft motor grader (425)	3 wheel roller (539)

Table 3.1d: Technical packages for gravel surfacing in the 1920's, 1950's and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Spreading Gravel	Equipment: Compacting Gravel
1970: 32	Skilled	12 ft motor grader (425)	Pneumatic roller (537)
33	Skilled	12 ft motor grader (425)	Vibratory roller (538)
41	Skilled	14 ft motor grader (426)	3 wheel roller (539)
42	Skilled	14 ft motor grader (426)	Pneumatic roller (537)
43	Skilled	14 ft motor grader (426)	Vibratory roller (538)
51	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	3 wheel roller (539)
52	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (537)
53	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Vibratory roller (538)

Note: All technical packages also include gravel (830).

Table 3.1e: Technical packages for waterbound macadam surfacing in the 1920's, 1950's, and 1970's.

Period and No. of Technical Package	Labor	Equipment		
		Spreading Crushed Stone	Spreading Screenings	Sprinkling and Compacting
1920: 111	Skilled Unskilled	Handtools (401)	Handtools (401)	3 wheel roller (531) Sprinkler wagon (405) Horse
211	Skilled Unskilled	5 ft blade grader (404) Horse Handtools (401)	Handtools (401)	3 wheel roller (531) Sprinkler wagon (405) Horse
1950: 111	Skilled Unskilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	Spreader box (409) 10 ton truck (332) Handtools (408)	3 wheel roller (534) Water tank (407) 3.5 ton truck (334)
112	Skilled Unskilled	70 hp crawler tractor (641) 8 ft bulldozer blade (607)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533) Water tank (407) 3.5 ton truck (334)
211	Skilled Unskilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	Spreader box (409) 10 ton truck (332) Handtools (408)	3 wheel roller (534) Water tank (407) 3.5 ton truck (334)
212	Skilled Unskilled	130 hp crawler tractor (643) 11.5 ft bulldozer blade (609)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533) Water tank (407) 3.5 ton truck (334)
311	Skilled Unskilled	10 ft blade grader (420)	Spreader box (409) 10 ton truck (332) Handtools (408)	3 wheel roller (534) Water tank (407) 3.5 ton truck (334)

Table 3.1e: Technical packages for waterbound macadam surfacing in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment		
		Spreading Crushed Stone	Spreading Screenings	Sprinkling and Compacting
1950: 312	Skilled Unskilled	10 ft blade grader (420)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533) Water tank (407) 3.5 ton truck (334)
411	Skilled Unskilled	13 ft blade grader (421)	Spreader box (409) 10 ton truck (332) Handtools (408)	3 wheel roller (534) Water tank (407) 3.5 ton truck (334)
412	Skilled Unskilled	13 ft blade grader (421)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533) Water tank (407) 3.5 ton truck (334)
511	Skilled Unskilled	Gas spreader (422) 20 ton truck (333) Handtools (408)	Spreader box (409) 10 ton truck (332) Handtools (408)	3 wheel roller (534) Water tank (407) 3.5 ton truck (334)
512	Skilled Unskilled	Gas spreader (422) 20 ton truck (333) Handtools (408)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533) Water tank (407) 3.5 ton truck (334)
1970: 111	Skilled Unskilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Gas spreader (427) 20 ton truck (339) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
112	Skilled Unskilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)

Table 3.1e: Technical packages for waterbound macadam surfacing in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment		
		Spreading Crushed Stone	Spreading Screenings	Sprinkling and Compacting
1970: 113	Skilled Unskilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
121	Skilled Unskilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Spreader box (411) 10 ton truck (337) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
122	Skilled Unskilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)
123	Skilled Unskilled	180 hp crawler tractor (645) 12 ft bulldozer blade (616)	Spreader box (411) 10 ton truck (337) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
211	Skilled Unskilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Gas spreader (427) 20 ton truck (339) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
212	Skilled Unskilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)

Table 3.1e: Technical packages for waterbound macadam surfacing in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment		
		Spreading Crushed Stone	Spreading Screenings	Sprinkling and Compacting
1970: 213	Skilled Unskilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
221	Skilled Unskilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Spreader box (411) 10 ton truck (337) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
222	Skilled Unskilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)
223	Skilled Unskilled	385 hp crawler tractor (654) 14 ft bulldozer blade (617)	Spreader box (411) 10 ton truck (337) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
311	Skilled Unskilled	12 ft motor grader (425)	Gas spreader (427) 20 ton truck (339) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
312	Skilled Unskilled	12 ft motor grader (425)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)
313	Skilled Unskilled	12 ft motor grader (425)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)

Table 3.1e: Technical packages for waterbound macadam surfacing in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment		
		Spreading Crushed Stone	Spreading Screenings	Sprinkling and Compacting
1970: 321	Skilled Unskilled	12 ft motor grader (425)	Spreader box (411) 10 ton truck (337) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
322	Skilled Unskilled	12 ft motor grader (425)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)
323	Skilled Unskilled	12 ft motor grader (425)	Spreader box (411) 10 ton truck (337) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
411	Skilled Unskilled	14 ft motor grader (426)	Gas spreader (427) 20 ton truck (339) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
412	Skilled Unskilled	14 ft motor grader (426)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)
413	Skilled Unskilled	14 ft motor grader (426)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
421	Skilled Unskilled	14 ft motor grader (426)	Spreader box (411) 10 ton truck (337) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
422	Skilled Unskilled	14 ft motor grader (426)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)

Table 3.1e: Technical packages for waterbound macadam surfacing in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package	Labor	Equipment: Spreading Crushed Stone	Equipment: Spreading Screenings	Equipment: Sprinkling and Compacting
1970: 423	Skilled Unskilled	14 ft motor grader (426)	Spreader box (411) 10 ton truck (337) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
511	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Gas spreader (427) 20 ton truck (339) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
512	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343)
513	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)
521	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Spreader box (411) 10 ton truck (337) Handtools (410)	3 wheel roller (539) Water tank (412) 4 ton truck (343)
522	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (537) Water tank (412) 4 ton truck (343
523	Skilled Unskilled	Gas spreader (427) 20 ton truck (339) Handtools (410)	Spreader box (411) 10 ton truck (337) Handtools (410)	Vibratory roller (538) Water tank (412) 4 ton truck (343)

Note: All technical packages also include crushed stone (831), screenings (832), and water (833).

Table 3.1f: Technical packages for double bituminous surface treatment in the 1920's, 1950's, and 1970's.

Period and No. of Technical Package		Labor	Equipment: Sweeping the Base	Equipment: Distributing Bitumen	Equipment: Spreading Crushed Stone	Equipment: Compacting
1920:	1111	Skilled Unskilled	Handtools (401)	600 gal pressure distributor (450)	Handtools (401)	6 ton roller (530)
	1121	Skilled Unskilled	Handtools (401)	600 gal pressure distributor (450)	Spreader box (406) 5 ton truck (331) Handtools (401)	6 ton roller (530)
1950:	1111	Skilled Unskilled	Drag broom (440) Pickup truck (335)	1000 gal bitumen distributor (452)	Gas spreader (422) 20 ton truck (333) Handtools (408)	Tandem roller (535)
	1112	Skilled	Drag broom (440) Pickup truck (335)	1000 gal bitumen distributor (452)	Gas spreader (422) 20 ton truck (333) Handtools (408)	Pneumatic roller (533)
	1121	Skilled Unskilled	Drag broom (440) Pickup truck (335)	1000 gal bitumen distributor (452)	Spreader box (409) 10 ton truck (332) Handtools (408)	Tandem roller (535)
	1122	Skilled Unskilled	Drag broom (440) Pickup truck (335)	1000 gal bitumen distributor (452)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533)
	2111	Skilled Unskilled	Power broom (451)	1000 gal bitumen distributor (452)	Gas spreader (422) 20 ton truck (333) Handtools (408)	Tandem roller (535)
	2112	Skilled Unskilled	Power broom (451)	1000 gal bitumen distributor (452)	Gas spreader (422) 20 ton truck (333) Handtools (408)	Pneumatic roller (533)

Table 3.1f: Technical packages for double bituminous surface treatment in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package		Labor	Equipment: Sweeping the Base	Distributing Bitumen	Spreading Crushed Stone	Compacting
1950:	2121	Skilled Unskilled	Power broom (451)	1000 gal bitumen distributor (452)	Spreader box (409) 10 ton truck (332) Handtools (408)	Tandem roller (535)
	2122	Skilled Unskilled	Power broom (451)	1000 gal bitumen distributor (452)	Spreader box (409) 10 ton truck (332) Handtools (408)	Pneumatic roller (533)
1970:	1111	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1000 gal bitumen distributor (454)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Tandem roller (540)
	1112	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1000 gal bitumen distributor (454)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (541)
	1121	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1000 gal bitumen distributor (454)	Spreader box (411) 10 ton truck (337) Handtools (410)	Tandem roller (540)
	1122	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1000 gal bitumen distributor (454)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (541)
	1211	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1500 gal bitumen distributor (453)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Tandem roller (540)
	1212	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1500 gal bitumen distributor (453)	Gas spreader (427) 20 ton truck (339) Handtools (410)	Pneumatic roller (541)

Table 3.1f: Technical packages for double bituminous surface treatment in the 1920's, 1950's, and 1970's (continued).

Period and No. of Technical Package		Labor	Equipment			
			Sweeping the Base	Distributing Bitumen	Spreading Crushed Stone	Compacting
1970:	1221	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1500 gal bitumen distributor (453)	Spreader box (411) 10 ton truck (337) Handtools (410)	Tandem roller (540)
	1222	Skilled Unskilled	Rotary broom (441) 60 fwhp tractor (655)	1500 gal bitumen distributor (453)	Spreader box (411) 10 ton truck (337) Handtools (410)	Pneumatic roller (541)

Note: All technical packages also include crushed stone (834) and bitumen (835).

stage in the order given in Table 3.1, and a change in a digit reflects a change in the resource mix for that particular activity or task; the numbering scheme starts over with each period and with each stage. Site preparation, for example, consists of two major activities, brush and tree removal and burning of the debris; in 1920, there are two technical packages, which differ only in the resource mix for the first of these activities. The numbers in parentheses following each piece of equipment and each material in Table 3.1 are their resource numbers; Section 3.12 and Appendix B give further descriptive and quantitative details on all of the resources. Finally, it should be noted that there is a separate list of technical packages for each surfacing material since each requires somewhat different activities and thus different resources, while there is only one list for excavation/hauling and spreading/compaction since the same resources can often be used for various haul distances and degrees of compaction, resulting only in a change in the productivities of the resources.

3.12 Evaluation of Resource Productivities and Costs

Labor, equipment, and materials constitute the resources used in highway construction; a list of their various categories is included as Table 3.2 which also indicates the organization of their resource numbers. Labor is divided into two categories: (1) skilled which includes all heavy equipment operators, drivers of trucks over five cubic yards in capacity, and persons acting in a supervisory capacity on operations done predominantly by unskilled labor; and (2) unskilled

Table 3.2: The categories of labor, equipment, and materials used in highway construction.

1 -- Labor

01	skilled
02	unskilled

2 -- Excavate, Load Equipment

01-29	unpowered
30-99	powered

3 -- Transport Equipment

01-29	unpowered
30-99	powered

4 -- Spread, Mix, Heat Equipment

01-19	earthwork and soil/aggregate surface treatments - unpowered
20-39	earthwork and soil/aggregate surface treatments - powered
40-49	bituminous surface treatments - unpowered
50-69	bituminous surface treatments - powered
70-79	concrete surface treatments - unpowered
80-99	concrete surface treatments - powered

5 -- Compact, Finish Equipment

01-29	unpowered
30-99	powered

6 -- Multi-Purpose Equipment

01-29	unpowered
30-99	powered

7 -- Miscellaneous Equipment

8 -- Materials

01-19	equipment consumables
20-29	materials aiding in construction
30-99	construction materials

Note: The horse is included as item 601, although it is handled separately in the analysis.

which also includes semiskilled and thus involves common heavy construction laborers, operators of small power tools, drivers of trucks five cubic yards and under in capacity, and drivers of horses, although there are a few exceptions in the 1920's. Equipment is divided into several categories on the basis of the activities in which it is involved. Materials consist of three categories: (1) equipment consumables such as fuel; (2) materials used as aids in construction such as explosives; and (3) construction materials such as aggregate. Lists of all equipment and materials are given in Tables B.2 and B.4, respectively. It should be noted that for each of the three technology periods a separate set of equipment is specified, although this is not the case for labor and materials. This seems only logical in situations where new types of equipment appear; it is also thus in situations where a piece of equipment is apparently carried forward from one period to the next, in that it has likely undergone certain changes which have influenced its quality, productivity, and so forth, and it is thus a different piece of equipment than it was. In the case of labor and materials, this process of change over time is largely ignored, and the assumption made that the change in these resources has been of much less significance than that in equipment.

Resource productivities of the various technical packages available over time in the U.S. might most ideally be obtained from field observations of all packages at one point in time and space. This is obviously impossible, however, and even where some of the older methods might still be in use, as in certain developing countries, it is generally in con-

junction with today's designs which raises a compatibility question, and the institutional and environmental conditions, which play an important role in resource productivity, are undoubtedly rather different. Since cross-sectional data is thus not available, historical has to suffice, although inherent in it are such problems as changes in resource quality, indexing difficulties, lack of detail, and questionable reliability.

In the course of searching for this data, various agencies such as the FHWA and U.S. Bureau of Labor Statistics, associations such as the Associated General Contractors of America, American Road Builders Association, and Construction Industry Manufacturers Association, and equipment manufacturers such as Caterpillar Tractor Company and John Deere were contacted. A thorough search of the literature was also undertaken, including the publications of various groups such as the FHWA, Transportation Research Board, National Cooperative Highway Research Program, American Association of State Highway and Transportation Officials, and American Society of Civil Engineers, the publications of the Engineering Experimental Stations of various universities such as Purdue and Iowa State, various books and handbooks pertaining to highways and their construction including those focusing on methods and costs, cost estimating, engineering, and equipment, and various journals such as Public Roads, Construction Methods and Equipment, and Highway and Heavy Construction. The single most useful source for the productivity data is probably the FHWA production studies noted above, although the various books and handbooks are also very valuable.

The productivities of the labor, equipment, and materials included

in each technical package are usually derived from a variety of sources, generally at the activities level, under typical institutional and environmental conditions, for each stage of construction for the 1920's, 1950's, and 1970's. Section B.12 contains sample calculations of these productivity figures, demonstrating the estimation procedure and also giving an indication of the range in quality and detail found in the original data; Table B.1, then, in Section B.13 lists the full set of estimated resource requirements of each technical package for all stages and all three periods, as well as identifying the sources for each technical package. In order to remain consistent and logical throughout the course of deriving the various resource productivities, certain assumptions were made at the outset and as necessary throughout this phase of the work; some of the more important ones are touched upon here in the following brief discussion of each stage of construction, while a more complete discussion of them and the sources substantiating them can be found in Section B.11 and in the sample calculations of Section B.12. It should be noted that all assumptions and productivity estimations are made with the project-level analysis in mind.

Site preparation consists of brush, tree, and stump removal and burning of the debris and is measured in hectares or acres, generally including the road and borrow areas. The environmental condition of primary concern here is the amount of vegetation which is taken as medium. As in the spreading/compaction and surfacing stages, the width of the road may be a factor in resource productivity; in such cases,

productivity data for the two road widths designed in Section 3.2 are calculated and averaged to get a figure relatively independent of road width.

Loosen and load constitute the first part of excavation/hauling, while load, haul, unload, and return constitute the second. The units of measure are bank cubic meters or bank cubic yards, and soil and haul distance and condition are the primary environmental factors. Ordinary/common soil is assumed, which was later made more specifically silty clay, as this is one of only a few materials for which a relationship could be found in the literature between the amount of compaction and subgrade strength; these materials may be from cuts for the road itself or from borrow areas and may be going to the embankment or to spoil. As for the haul, the conditions are assumed to be average to good, and the distance is allowed to vary; in determining the haul distances for the two basic designs under various borrow situations given in Section 3.2, three groups of haul distances arose which in the stage-level analysis are represented by 6, 100, and 800 meter (20, 330, and 2625 foot) hauls.

Spreading/compaction is made up of the activities spread, compact, and finish, is also measured in bank cubic meters or bank cubic yards, and pertains to subgrade materials coming from cuts for the road or from borrow areas and going to fills for the embankment. In this stage, as in surfacing, the quality of the product may be dependent upon the the technology which produces it. Data on compaction for the 1920's is particularly sparse, but with the help of a British publication (70)

relating material density to number of passes for a few materials and rollers, two levels of compaction could be derived for the 1920's horse-drawn roller: (1) 98 percent compaction which falls within the range 95-100 percent of the standard AASHO compaction, the customary level of compaction of subgrades and embankments today, and which represents a compacted to loose ratio of 65 percent, assuming a bank to loose ratio of 80 percent for this soil; and (2) 93 percent compaction which falls below that generally acceptable today and which represents a compacted to loose ratio of 69 percent. The productivity of the powered roller in the 1920's, as well as that of all 1950's and 1970's rollers, is estimated only at 98 percent compaction, or as falling within the 95-100 percent range, as this can reasonably be achieved by such equipment.

The activities involved in surfacing vary with the material, as do naturally the quality of the product and the set of technical packages used in its construction. Spreading, compacting, and finishing the gravel constitute gravel surfacing, which is measured in compacted cubic meters or compacted cubic yards. Although the degree of compaction might again be allowed to vary, compaction in the range of 100-105 percent standard AASHO, as is customary for gravel subbases, bases, and surfaces, can reasonably be achieved by all rollers in the study, and this variable is thus assumed constant. The construction of water-bound macadam consists of spreading very coarse crushed rock, compacting, spreading screenings, and sprinkling, compacting, and finishing; it is measured in compacted cubic meters or compacted cubic yards.

According to the sources discussing waterbound macadam in the 1920's (11, 29), which is when it was most commonly used, nearly a hundred passes are necessary in the final compaction activity in order to properly float the mixture of screenings and water between the crushed rock as a binder; unfortunately, there is no indication of the surface behavior if less compaction is used, so this parameter could not be varied. Double bituminous surface treatment involves sweeping the base, spreading the primer bitumen, binder bitumen, and quite finely crushed stone, compacting (very lightly), spreading binder bitumen and even finer crushed stone, and compacting (very lightly) and finishing; since this is, as its name suggests, simply a surface treatment, it is measured in square meters or square yards, having a finished thickness of only some 2.2 centimeters (7/8 inch). The activities involved in materials production and their transport to the site are included in the cost of the materials rather than as a surfacing activity, although these activities also warrant investigation as to how their technology has changed.

These particular surfaces were selected because they are reasonably flexible in terms of the variety of technical packages that can be used in their construction, they represent a reasonable range of surface materials although they tend toward the low standard end for the 1950's and 1970's, and they were in use in all three periods although waterbound macadam is no longer much used except perhaps as a base. The materials productivity is thus based on designs which pretty much span all three periods. It should also be noted that it is assumed that the

same resource productivities apply whether the material is used as a surface, base, or subbase.

In addition to the stage-specific assumptions, some more generally applicable ones are also necessary. At least in part in order to avoid grossly different environmental and particularly institutional conditions, the study is limited to the U.S.; it thus seems appropriate, within reason, to assume that the health and nutritional conditions, work attitudes, and basic quality of the workforce are relatively uniform, the work is generally performed on a contract basis and payment of labor is by the hour, the equipment is reasonably fully utilized, and the climate is temperate. It is also assumed that the necessary amenities for labor and maintenance and repair facilities for equipment are available, and that the costs of these and of mobilization of labor and equipment essentially balance out for the two resources and are thus not explicitly included. Management is assumed to be average to good, working efficiency to be 80 percent (i.e., a 48-minute hour) when it is not specified for the particular operation, and supervision to be one supervisory person per a crew of ten or so unskilled men in situations where the workforce is predominantly unskilled laborers, mostly arising in the 1920's technical packages. Finally, the parameters of time to complete the job and project scale are not considered, as data are lacking and they are beyond the scope of this analysis.

At this point the resource productivities, in hours of labor or equipment per unit of output or quantity of material per unit of output, have been derived; what is still required for the determination of

the unit costs of the various technical packages (i.e., dollars per unit of output) are the resource costs, in dollars per hour for labor and equipment or dollars per quantity of material. These costs are needed for a few points in time; more specifically, since the influence of resource prices and thus factor substitution on technology change is of interest in this study, sets of resource costs representative of each technology period are necessary. The prices of 1930, 1956, and 1974 are thus used throughout the analysis. The economic situation at the time of the 1920's technology makes selection of a year rather difficult; however, since equipment purchase costs are mostly available for 1930 and only an extrapolated form of the equipment index exists prior to 1929, 1930 seems an appropriate year, a time when prices were on the decline but had not yet reached the bottom. The year 1974 is selected as the most current year for which a full set of cost data would be available. Finally, 1956 is selected as being in a relatively similar position, some two-thirds of the way through the time span covered by the technology period. The difficulty, of course, is arriving at a full set of labor, equipment, and materials prices for these particular years, necessitating a further search of the literature and pursuit of various contacts in the field.

Equipment is the most difficult resource to price, its hourly price involving ownership costs of depreciation and interest, maintenance, and miscellaneous items such as insurance, tax, and storage and operating costs of fuel and lubrication. Hourly rates for equipment may be found throughout the literature in various forms (e.g., hourly ownership cost

and fuel consumption), but because of the various assumptions hidden in such figures and the difficulty of adjusting them to various time periods, it was decided to estimate hourly equipment rates from scratch. This necessitated the collection of certain basic data about each piece of equipment, including investment cost, life in years, hours used per year, maintenance as a percentage of investment cost, and rate of fuel consumption, and certain assumptions such as the use of a capital recovery factor to arrive at interest and depreciation, selection of 5.5 percent of average annual investment as the charge for miscellaneous items, and estimation of lubrication as 35 percent of fuel cost. The basic data for each piece of equipment, with the possible exception of the rate of fuel consumption, by and large came from a single source for each technology period. The Associated General Contractors of America were responsible for the 1920's source (5), while Peurifoy authored both the 1950's and 1970's sources (66, 67); the data presented in each are similar enough in form to suggest that there may be a certain amount of coordination. Adjusting the hourly rate to various price periods simply involves adjusting the investment cost, interest rate, and fuel cost. Since each piece of equipment is taken as somewhat unique to its time period, its purchase price at the time of its use is inflated or deflated by means of an index. For the period 1929-1965, the U.S. Office of Business Economics index for private purchases of construction machinery (110) is directly used; the U.S. Bureau of Labor Statistics wholesale price index (91) for construction machinery and equipment is used to extrapolate this index forward from 1965, and

the same index for industrial commodities to extrapolate it backward from 1929, resulting in an index covering the entire period 1913-1974. Interest rates for the three years are taken from the Federal Reserve Bulletin's statistical tables (26), while fuel is costed as a material. For further details on any aspect, see Section B.21.

The draft animal, a horse in this study, is part of many of the 1920's technical packages; although it is in essence a piece of equipment, it is treated separately here as its cost is derived somewhat differently. An investment cost and hourly rate including upkeep are obtained for the 1920's and are inflated as necessary using the U.S. Bureau of Labor Statistics wholesale price indexes (91).

Labor and materials are handled very similarly. Prices are obtained for each of the three periods with only occasional use of indexes (the wholesale price indexes of the U.S. Bureau of Labor Statistics [91, 96]), and the same basic source is used to price a particular item over as many periods as possible (e.g., materials quotations in the Engineering News-Record [25] are used to price all but a couple of the construction materials for all three periods). The primary sources include Engineering News-Record (25), U.S. Bureau of Labor Statistics (91, 96), Survey of Current Business (78) and one of its supplements (109), and certain of the sources for resource productivities especially for the 1930's prices (e.g., 29). The hourly rate for skilled and unskilled labor is that which the contractor pays out for union labor for 1956 and 1974; the same source was not available for 1930, however, and it seems likely that the wage rate which is used is a mix of union and nonunion rates. As for materials, wholesale prices are

used, and the price for construction materials includes delivery as well as production. For further discussion of pricing the horse, labor, and materials see Sections B.22, B.23, and B.24, respectively.

As discussed in the methodology of the data analysis in Section 2.3, a wide range of economic conditions is needed in order to ascertain the set of efficient technical packages for each stage of construction, for each period and over all periods. The set of economic conditions developed for this purpose is given in Table 3.3. The figures for the U.S. for 1930, 1956, and 1974 and for a developing country today come directly from the tables and discussion in Section B.2. It should be noted that these conditions reflect a rather extreme case of a developing country. The wage rates reflect an abundance of unskilled labor and a relative shortage of skilled labor, while the interest rate suggests a lack of capital; the prices of heavy equipment (i.e., powered equipment or unpowered equipment attached, in some way, to powered equipment), equipment consumables, and materials assisting in construction suggest they are imported, while the price of light equipment (i.e., unpowered equipment or that which may be animal-powered) suggests it is locally produced, and that of the horse that it is relatively available. The set of miscellaneous conditions exists for the purpose of developing alternative combinations and conditions within the four groups of factors; the interest rate and labor wages represent an even more extreme case of a developing country. It might also be noted that construction materials are missing from the list in Table 3.3; these materials are not needed for the stage-level analysis, as materials productivity is assumed to be constant over all relevant technical packages,

Table 3.3: The set of economic conditions used in the efficiency analysis at the stage level (Source: Section B.2).

		Economic Conditions				
		United States			Developing	Miscellan-
Resource	Units	1930	1956	1974	Country	eous
1. Labor - skilled	$/hr	0.88	3.17	9.86	0.20	0.75
- unskilled	$/hr	0.46	2.36	7.88	0.05	0.01
2. Interest Rate	%	5.0	4.5	11.5	20.0	30.0
3. Equipment - light	index	30.1	89.7	176.3	15.0	-
- heavy	index	30.1	89.7	176.3	350.0	-
Coal	$/ton	4.00	8.91	32.97	40.00	-
Gasoline	$/gal	0.194	0.25	0.426	2.00	-
Diesel Fuel	$/gal	0.091	0.15	0.355	1.50	-
Dynamite	$/lb	0.206	0.248	0.321	0.500	-
Fuse	$/100 ft	0.71	1.22	3.44	4.00	-
Caps	$/100 count	1.08	1.85	5.22	6.00	-
Kerosene	$/gal	0.057	0.103	0.232	0.700	-
4. Horse	$/hr	0.12	0.22	0.44	0.05	-

Note: Light equipment is unpowered equipment or that which may be towed by horses, while heavy equipment is powered or unpowered equipment which is somehow attached to powered equipment. The ratio of the index given in this table to that at the time a particular piece of equipment was in use is used to inflate or deflate the investment cost of that particular piece of equipment at the time of its use.

and comparisons among various types of surfaces are relatively meaningless at the stage level since their quality varies.

3.13 Alternative Technical Packages and Their Costs

As a first step in the analysis of the alternative technical packages and their costs, Figure 3.1 presents a graphical representation of some of the results. For each stage of construction and each technology period, the amount of investment in 1974 dollars and the amount of labor required to achieve a certain rate of production is plotted for each technical package. The labor component is measured in terms of unskilled men which is derived by summing over the number of skilled men, weighted by the ratio of skilled to unskilled wages for the period of the technology, and the number of unskilled men; the rate of production is expressed in basically arbitrary hourly units, being, for example, 100 bank cubic meters per hour for excavation/hauling and spreading/compaction. Here, as throughout the remainder of the analysis, various haul distances, levels of compaction, and surfacing materials are handled separately, as these parameters affect the resource productivities and thus costs. Such a pictorial representation of the alternative technical packages is useful in terms of developing a general impression of how technology has changed. Moreover, if it can reasonably be assumed that investment is an appropriate measure of capital, as is often done in the economic literature and as is discussed further for the case at hand in Section 4.11, then these graphs are production isoquants, depicting the set of efficient technical packages for each stage of construction for

Figure 3.1a: Labor and capital requirements of each technical package for site preparation at the rate of 1 hectare per hour, for each technology period (source: Table B.6).

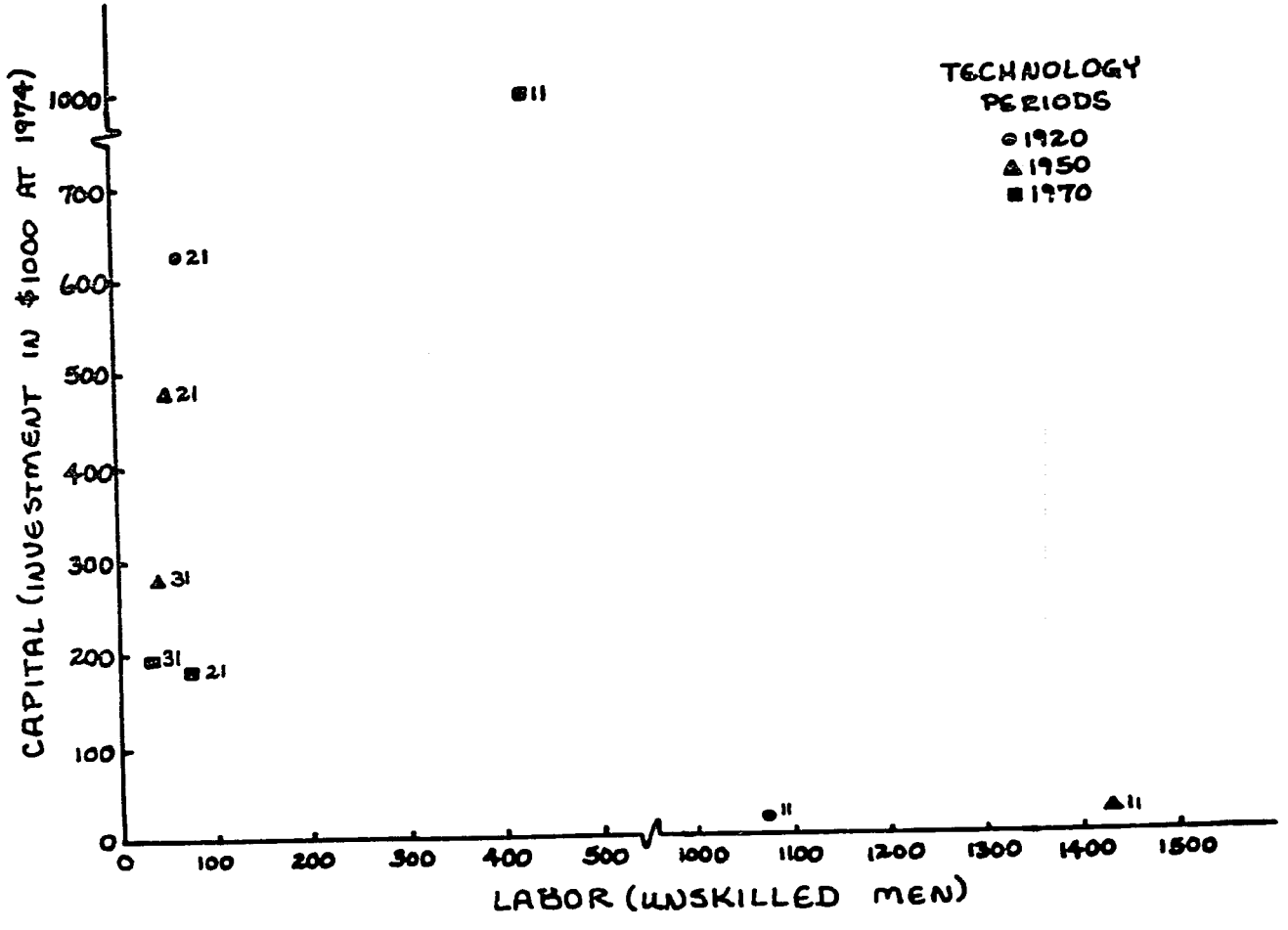


Figure 3.1ba: Labor and capital requirements of each technical package for excavation/hauling at 6 meters at the rate of 100 bank cubic meters per hour, for each technology period (source: Table B.6).

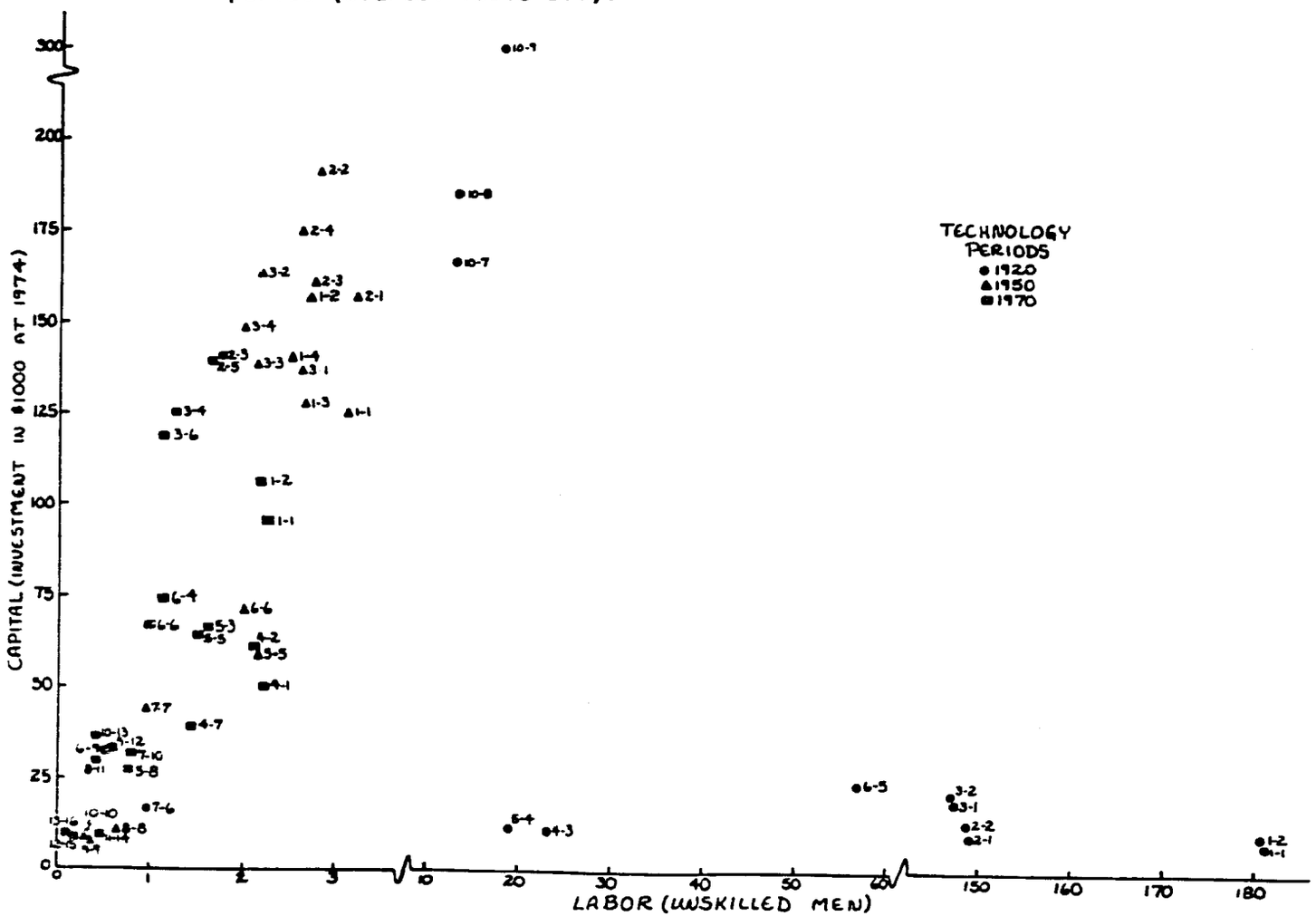


Figure 3.1bb: Labor and capital requirements of each technical package for excavation/hauling at 100 meters at the rate of 100 bank cubic meters per hour, for each technology period (source: Table B.6).

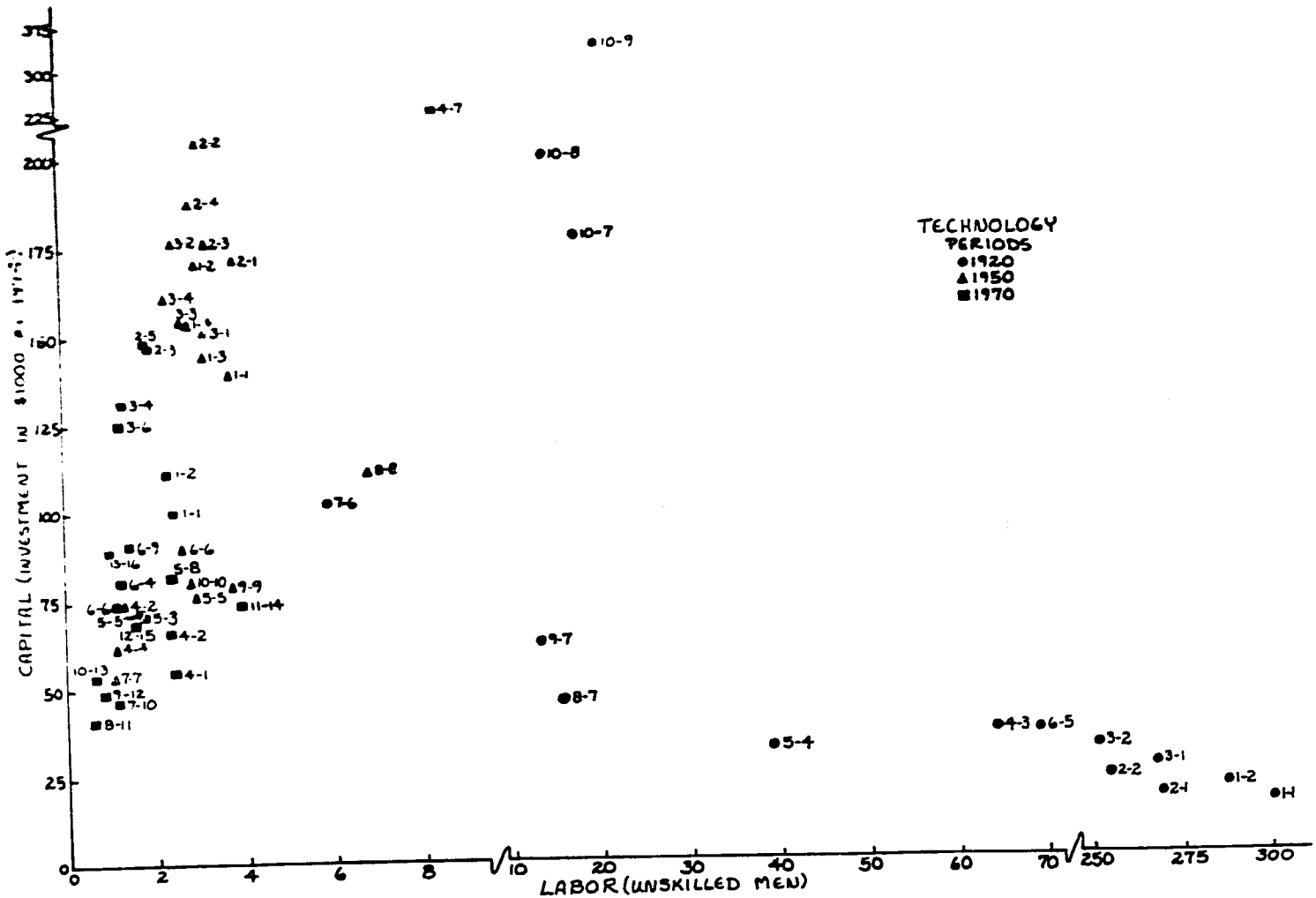


Figure 3.1bc: Labor and capital requirements of each technical package for excavation/hauling at 800 meters at the rate of 100 bank cubic meters per hour, for each technology period (source: Table B.6).

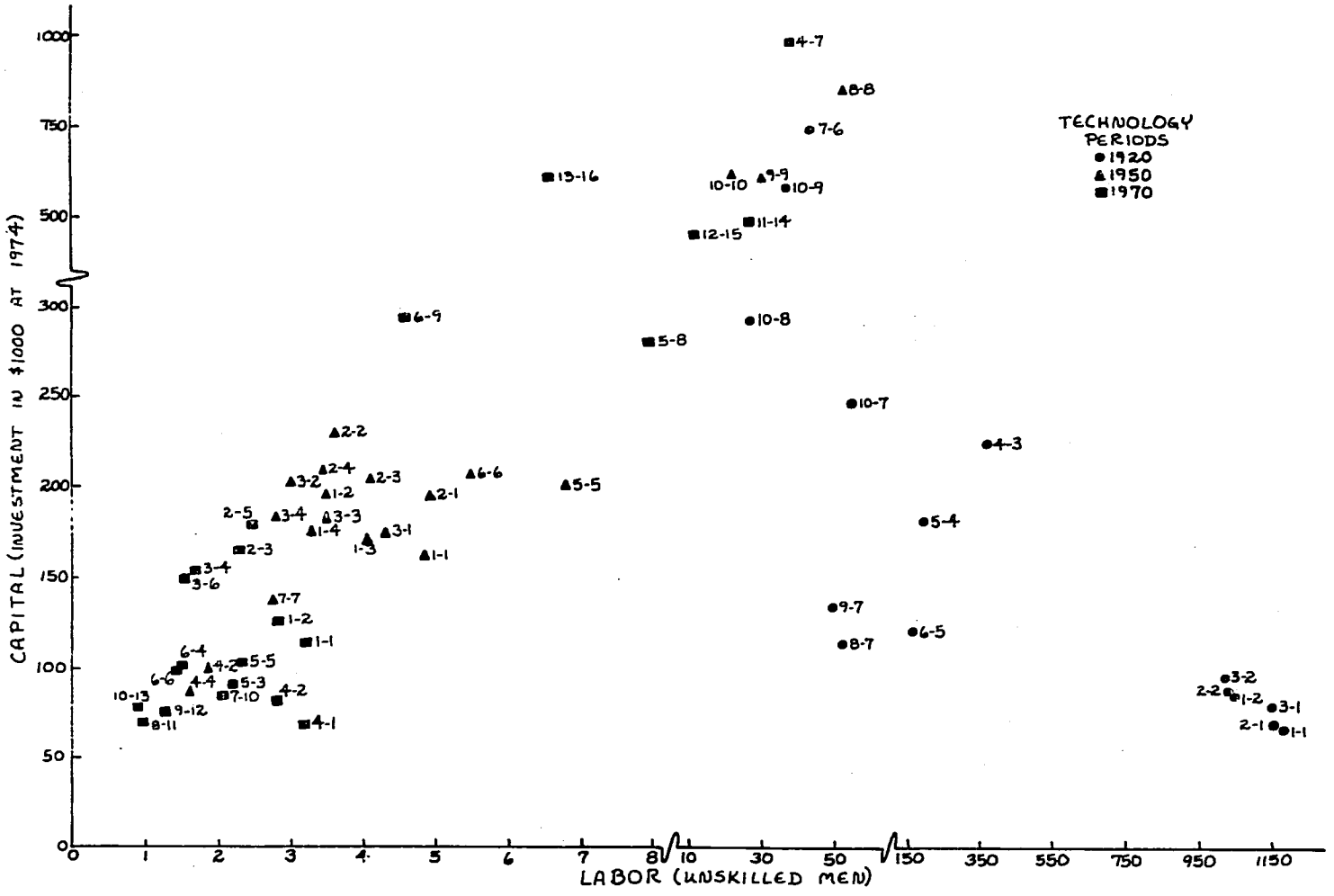


Figure 3.1c: Labor and capital requirements of each technical package for spreading/compaction at the rate of 100 bank cubic meters per hour, for each technology period (source: Table B.6).

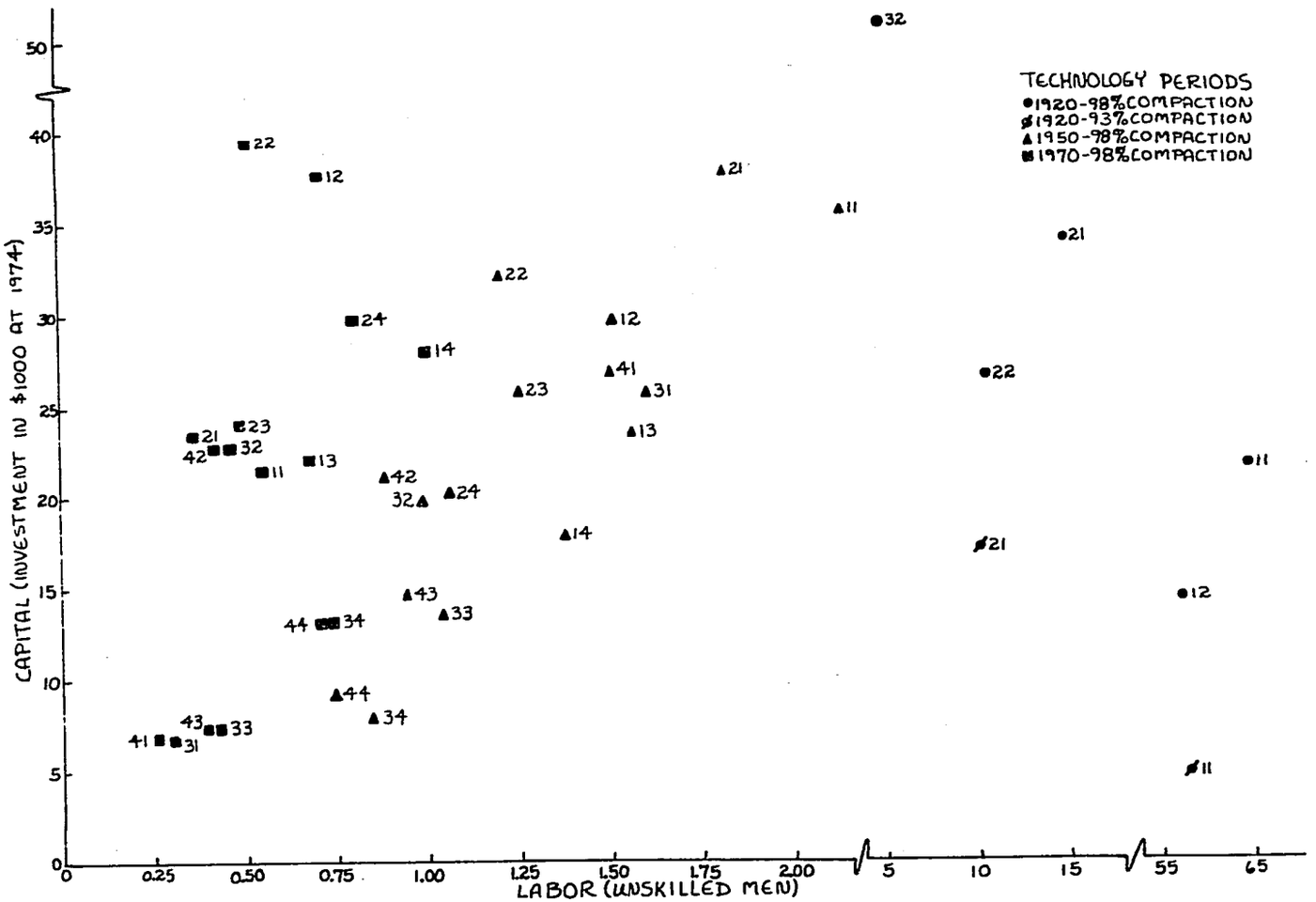


Figure 3.1d: Labor and capital requirements of each technical package for gravel surfacing at the rate of 100 compacted cubic meters per hour, for each technology period (source: Table B.6).

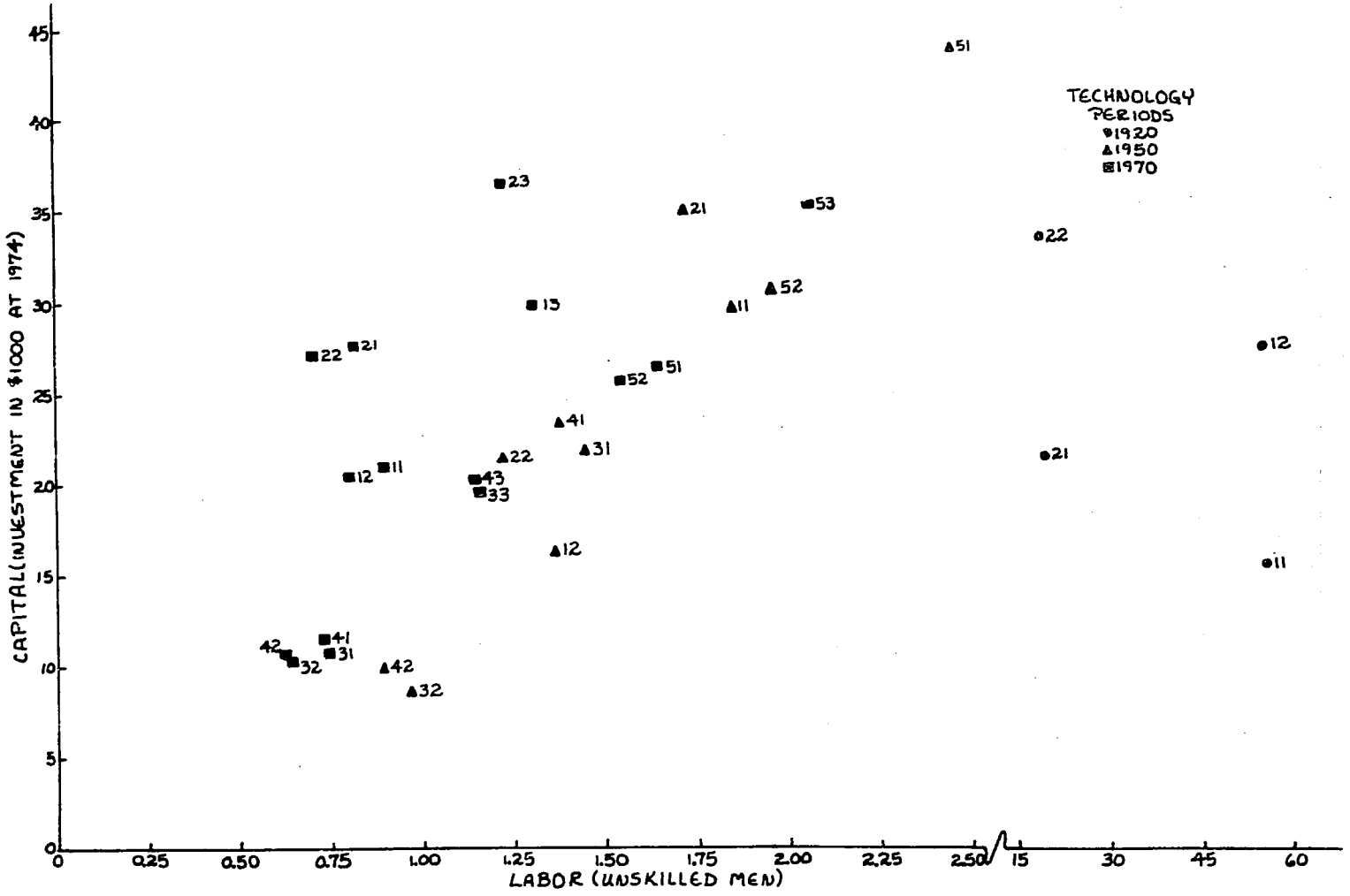


Figure 3.1e: Labor and capital requirements of each technical package for waterbound macadam surfacing at the rate of 100 compacted cubic meters per hour, for each technology period (source: Table B.6).

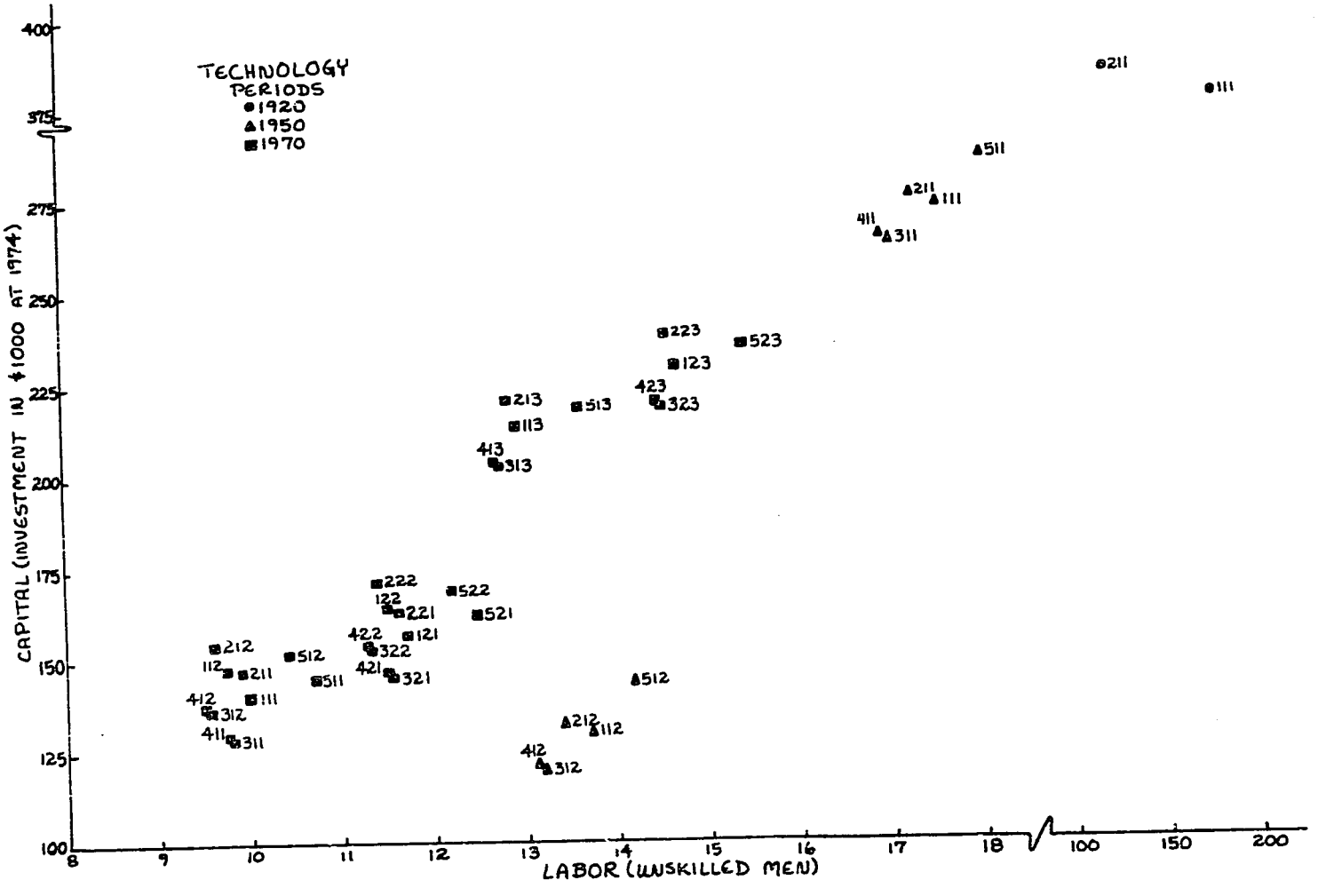
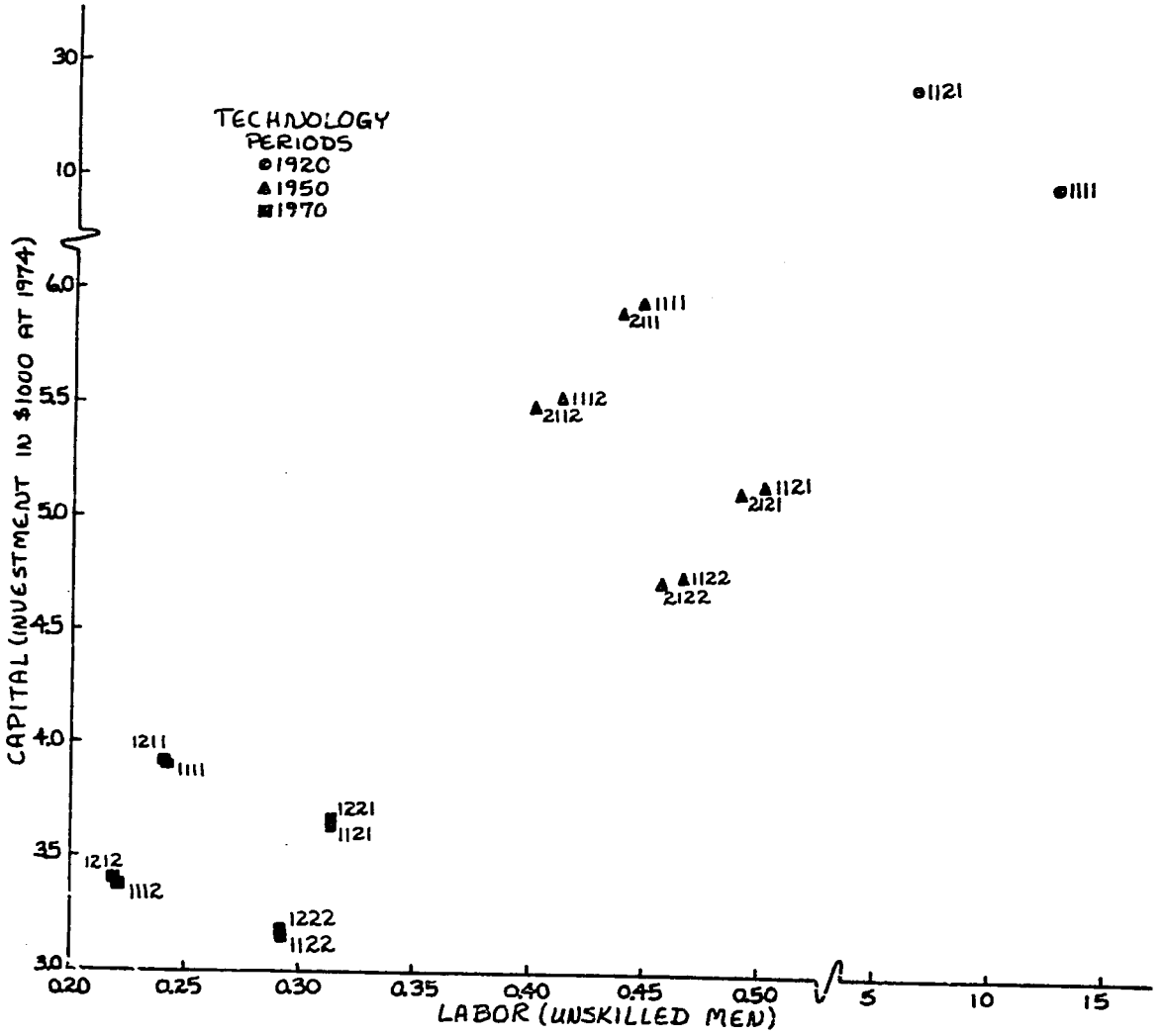


Figure 3.1f: Labor and capital requirements of each technical package for double bituminous surface treatment over gravel at the rate of 100 square meters per hour, for each technology period (source: Table B.6).



each technology period and over all periods; Table 3.4 summarizes these graphs by presenting the efficient set so determined in list form.

In situations where the lifetime, maintenance as a percentage of investment cost, and fuel consumption vary considerably among the different pieces of equipment, as is particularly the case for the 1920's (see Table B.2), a perhaps more reliable measure of capital is its hourly ownership and operating cost; a numerical, as opposed to graphical, efficiency analysis of the sort outlined in Section 2.31 thus becomes necessary. The results of this are included here as Table 3.5, where the set of efficient technical packages is given for each stage, for each technology period and over all periods. It should be noted, however, that this efficient set is restricted to those technical packages which arise as least cost under some reasonable mix of the economic conditions given in Table 3.3, and it may not thus be all-inclusive.

Four hundred possible combinations of economic conditions arise from the four groups of resources, each with four or five economic conditions. Certain combinations are, of course, not plausible, including for example:* (1) 1974 labor and 1930 equipment; (2) 1956 labor, miscellaneous interest rate, and 1930 equipment; and (3) miscellaneous labor and 1930 equipment; only three of the technical packages, which show up as being least cost under some of the four hundred combinations, appear only under such implausible combinations and are thus eliminated from the efficient set. Each of the technical packages in Table 3.5 thus

*Resource groups not included in the combination listed may take any value.

Table 3.4: Graphical efficiency analysis results -- the set of efficient technical packages for each stage of construction, from among those available in each technology period alone and in all periods combined (source: Figure 3.1 and Table B.6).

Stage	Technology Period			All Periods		
	1920	1950	1970	1920	1950	1970
Site Preparation	11,21	11,31	21,31	11	-	21,31
Excavation/Hauling						
-6M	1-1,4-3,5-4,7-6	9-9,10-10	12-15,13-16	-	9-9	12-15,13-16
-100M	1-1,5-4,7-6,8-7	7-7	8-11	1-1,5-4	-	8-11
-800M	1-1,8-7,10-8	4-4	4-1[a],8-11,10-13	1-1	-	4-1[a],8-11,10-13
Spreading/Compaction						
-93%	11,21	-	-	-	-	-
-98%	12,22,32	34,44	31[a],41	-	-	31[a],41
Gravel Surfacing	11,21,22	32,42	32,42	-	32	32,42
Waterbound Macadam Surfacing	111,211	312,412	311,312,411,412	-	312,412	311,312,411,412
Double Bituminous Surface Treatment over Gravel	1111,1121	2112,2122	1112,1122,1212,1222	-	-	1112,1122,1212, 1222

[a]These technical packages are barely efficient in that the investment costs of 800M exc/haul tp 8-11 and of 98% spr/comp tp 41 are only very slightly higher than those of tp 4-1 and tp 31, respectively, although their labor requirements are significantly less.

Table 3.5: Numerical efficiency analysis results -- the set of efficient technical packages for each stage of construction, from among those available in each technology period alone and in all periods combined.

Stage	Technology Period					
				All Periods		
	1920	1950	1970	1920	1950	1970
Site Preparation	11,21	31	31	11	-	31
Excavation/Hauling						
-6M	1-1,4-3,5-4,7-6	9-9,10-10	12-15,13-16	5-4	9-9	13-16
-100M	1-1,1-2,5-4,7-6,8-7,9-7	7-7	8-11	1-1,1-2,5-4,8-7	-	8-11
-800M	1-1,1-2,2-1,2-2,6-5,8-7, 9-7,10-8	4-4	8-11	1-1,1-2,2-1,2-2,8-7	-	8-11
Spreading/Compaction						
-93%	11,21	-	-	-	-	-
-98%	11,21,12,22,32	33,34,43,44	41	21	-	41
Gravel Surfacing	11,21,12,22	32,42	31,41	21	-	31,41
Waterbound Macadam Surfacing	111,211	312,412	311,411	-	-	311,411
Double Bituminous Surface Treatment over Gravel	1111,1121	2112,2122	1112,1121,1122	-	-	1112,1121,1122

arises under one or more sets of conditions constituting a reasonable scenario such as: (1) the U.S. in 1974, 1956, or 1930 or some slight variation (e.g., 1974 conditions except developing interest rate, 1956 conditions except 1930 interest rate and/or labor, or 1930 conditions except 1956 interest rate and/or developing horse and/or labor); (2) a reasonably typical developing country or some slight variation (e.g., 1930 or miscellaneous labor, miscellaneous interest rate, and/or 1974 equipment); (3) the U.S. in the future as labor continues to increase in cost relative to other resources (e.g., 1956 conditions except 1974 labor or 1930 conditions except 1956 labor); (4) a reasonably advanced developing country (e.g., 1930 labor, 1974 interest rate, 1956 equipment, and 1930, 1956, or developing horse); and (5) a capital-rich developing country with somewhat of a labor shortage (e.g., 1930 or 1956 labor and interest rate and 1974 or developing equipment) or with an abundance of unskilled and shortage of skilled labor (e.g., developing or miscellaneous labor, 1930, or 1956 interest rate, and 1974 or developing equipment). It is interesting to note that, except in a few cases, the most labor-intensive technical packages of the 1920's given in Table 3.5 arise only under the conditions given in (2) above with a 1956 or 1974 horse, suggesting the importance of the draft animal in raising crew productivity.

In order to begin to address the issue of efficiency and substitution and their role in technology change, it is necessary to apply, to the resource requirements of each of the technical packages in each technology period, the factor prices at each of the price periods; the set of unit costs, which constitute the results of this, are given in Table B.5.

Table 3.6, then, presents a subset of these results: the set of least-cost, and thus best-practice, technical packages for each stage of construction, at the prices of 1930, 1956, and 1974, in each of the 1920's, 1950's, and 1970's technology periods. Technical packages with unit costs within ten percent of that of the least-cost technical package are also included in Table 3.6 in order to allow for reasonable error, accounting for those cases where more than one technical package is listed for a particular technology and price period. Generally, a second technical package is the most that is necessary to include, with the exception of the waterbound macadam surfacing and double bituminous surface treatment stages; these two stages involve a greater number of major activities or tasks for which different resource packages can be specified, and thus each activity or task potentially has a lesser part in the whole, and correspondingly, a change in its resource package potentially has a lesser impact on total unit cost. All further analyses involving the best-practice packages include those which appear as least-cost at the prices of the period coincident with that of the technology; in cases where more than one package is involved, the data for the various packages is averaged as necessary for the analysis.

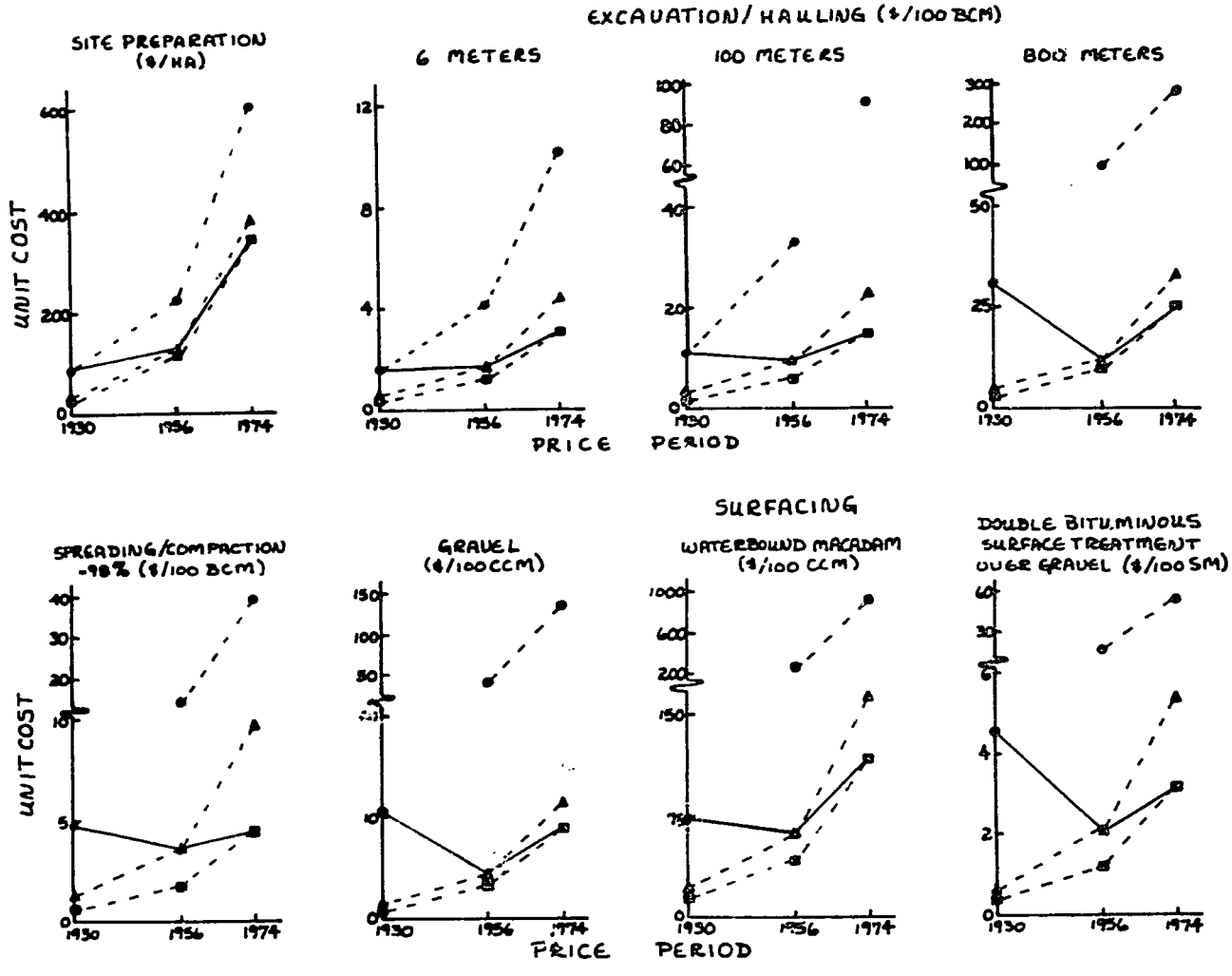
Figure 3.2 is presented to give some indication of the magnitude of technology change in unit cost terms. Figure 3.2a consists of plots, for each stage of construction, of the unit costs of the best-practice technical packages of each technology period at the prices of 1930, 1956, and 1974, indicating the transition in costs that actually occurred as well as that which would have occurred had technology not changed as it

Table 3.6: The set of least-cost technical packages for each stage of construction, at the prices of 1930, 1956, and 1974, from among those available in each technology period (source: Table B.5).

Stage	Technology Period		
	1920	1950	1970
Site Preparation	21	31	31
Excavation/Hauling			
-6M	7-6	9-9,10-10/10-10,9-9/10-10,9-9	13-16,12-15/13-16/13-16
-100M	7-6,9-7/7-6/7-6	7-7,4-4	8-11
-800M	10-8	4-4	8-11
Spreading/Compaction			
-93%	21	-	-
-98%	32	44/44,34/44,34	41,31
Gravel Surfacing	22	42,32	31,41
Waterbound Macadam Surfacing	211	412,312,212,112,512	311,411,111,211
Double Bituminous Surface Treatment over Gravel	1121	2122,1122,2121,1121,2112,1112/ 2122,1122,2112,1112,2121,1121, 2111,1111/2112,2122,1112,1122, 2111,2121,1111,1121	1122,1222,1112,1121,1212, 1221,1111,1211/1112,1212, 1111,1211,1122,1222,1121/ 1112,1212,1111,1211

Note: The slashes separate the packages which appear as least-cost at 1930/1956/1974 price periods; if there are no slashes, then the same packages appear as least-cost at each price period. The least-cost technical packages of the 1970's are least-cost among all technical packages at all three price periods. Least-cost includes those packages within 10 percent of the least-cost package, the order of the listing being from the lowest to highest in cost.

Figure 3.2a: Unit costs of the best-practice technical packages of each technology period for each stage of construction, at the prices of 1930, 1956, and 1974 (source: Table B.5).



(Figure 3.2a continued)

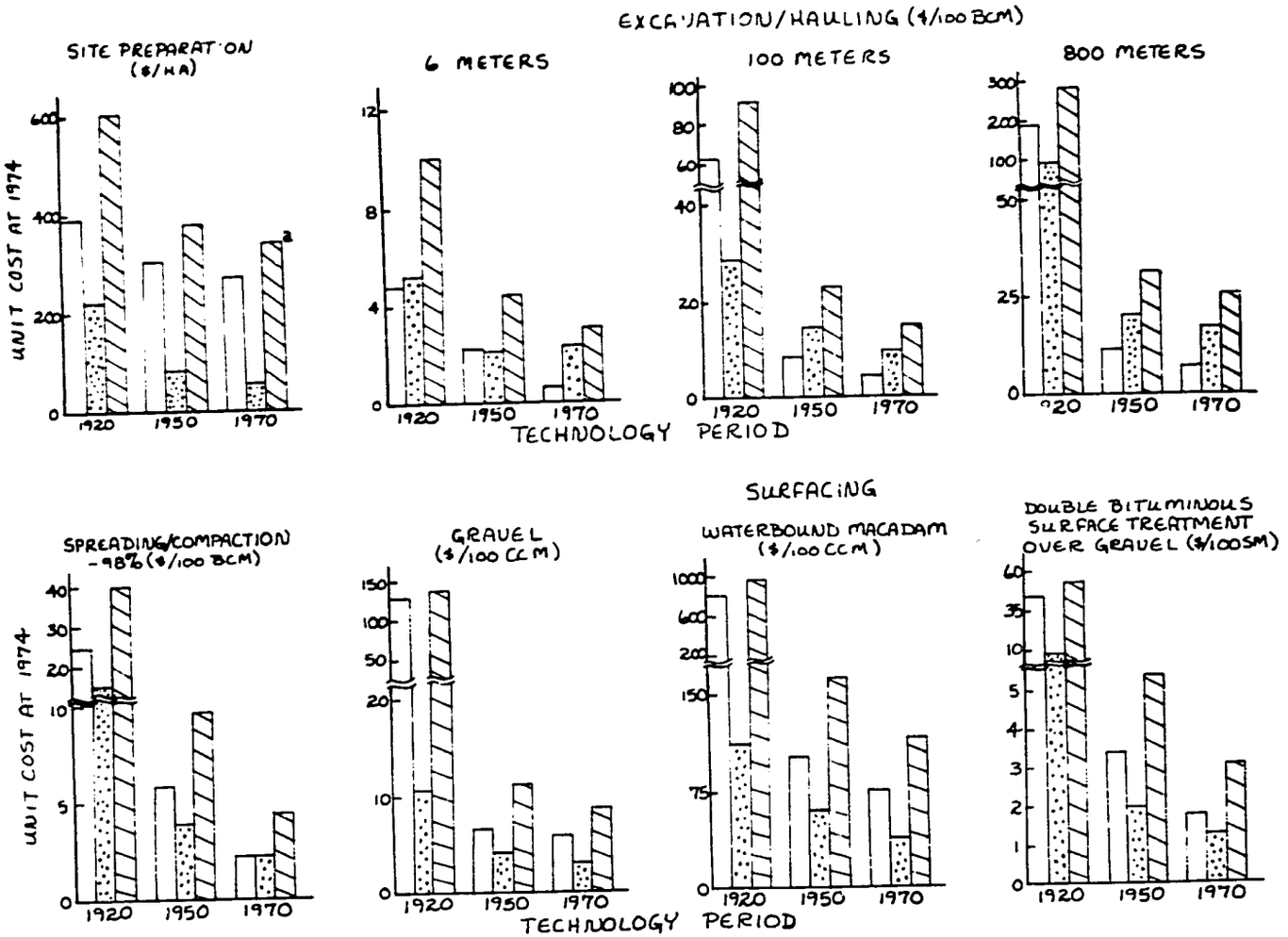
Note: Technology periods: ● 1920, ▲ 1950, ■ 1970.

——— Transition in costs that actually occurred.

- - - Transition in costs that would have occurred had technology not changed.

Best-practice packages are those which appear as least-cost, or within 10 percent of it, at the prices of the period coincident with that of the technology; where more than one package is involved, the data for the various packages is averaged.

Figure 3.2b: Labor and capital components of the unit costs of the best-practice technical packages of each technology period for each stage of construction, at the prices of 1974 (source: Table B.5).



(Figure 3.2b continued)

Note: Unit costs: ☐ labor, ⊡ capital, ▧ total.

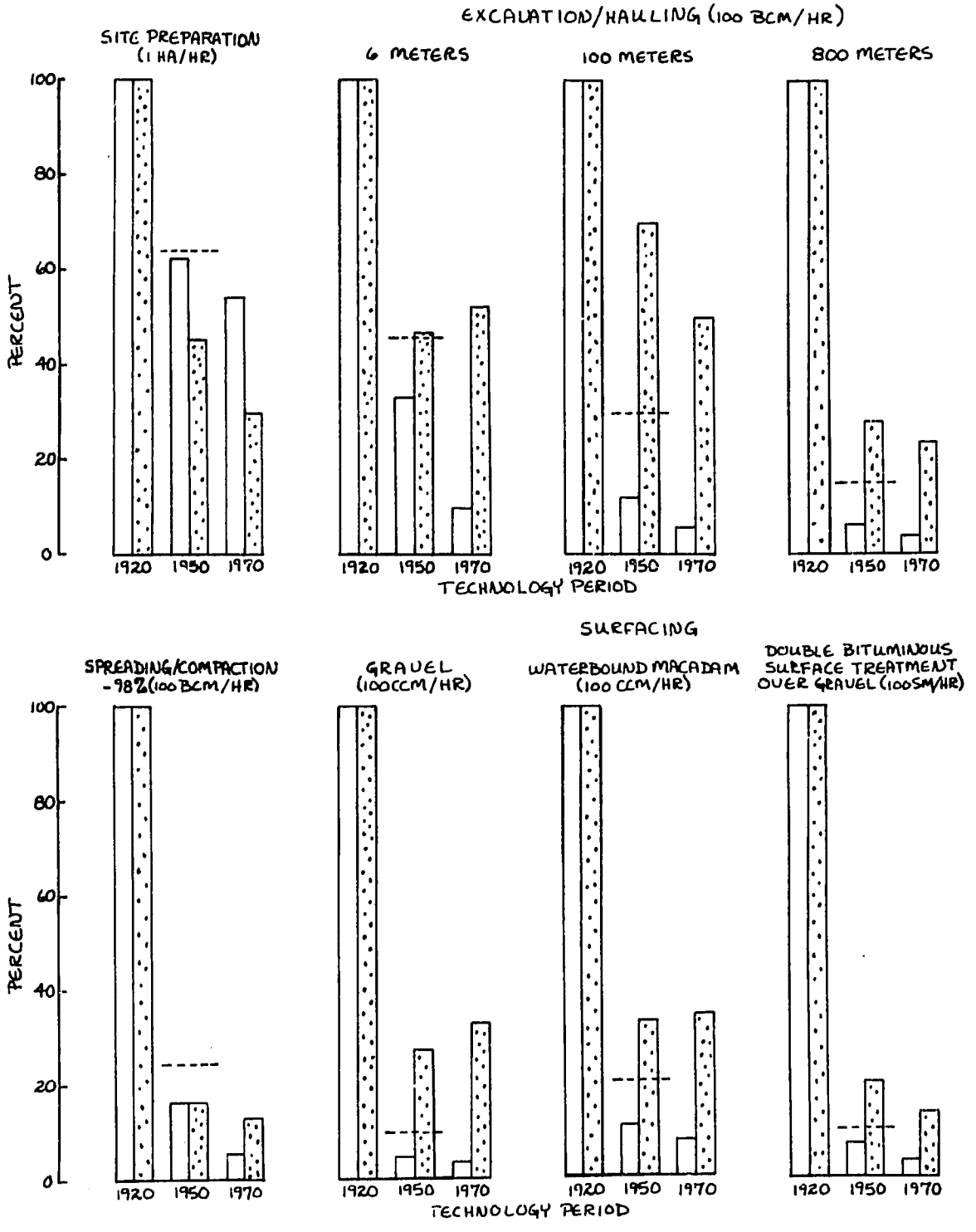
Best-practice packages are those which appear as least-cost, or within 10 percent of it, at the prices of the period coincident with that of the technology; where more than one package is involved, the data for the various packages is averaged.

[a]Includes $19.09 of materials.

did. In order to investigate labor and capital shares of the unit costs, Figure 3.2b presents bar charts, again for each stage, of the labor and capital components, in terms of 1974 unit costs, of the best-practice packages in each period. In an effort to avoid the biases introduced by the use of a particular set of factor prices and to focus more directly on changes in quantities of resources, Figure 3.3 uses labor measured in units of unskilled men and capital in 1974 investment dollars required for a particular rate of production; Figure 3.3a presents the labor and capital requirements of the best-practice packages of each of the three technology periods as a percentage of those of the 1920's, while Figure 3.3b does the same using the 1950's as the base.

Returning to the questions of efficiency and substitution and their role in technology change brings up Tables 3.6 and 3.7. Table 3.6 gives an indication of the extent of substitution, brought about by changes in factor prices, in technology change, as it gives the best-practice packages for each technology period at the prices of 1930, 1956, and 1974. In order to investigate the role of efficiency in technology change, a method based on that of Salter (73), as discussed in Section 2.31, is used to separate the impact of efficiency from that of bias, technology change being represented by movements among the best-practice packages over time. Table 3.7 presents the results of this analysis; the figures represent the percentage change (decrease [-] or increase [+]) in the quantity of labor and of capital, required for the various stages of construction, which can be attributed to efficiency and to

Figure 3.3a: Labor and capital requirements of the best-practice technical packages of each technology period as a percentage of those of the 1920's, for each stage of construction (source: Table B.6).



(Figure 3.3a continued)

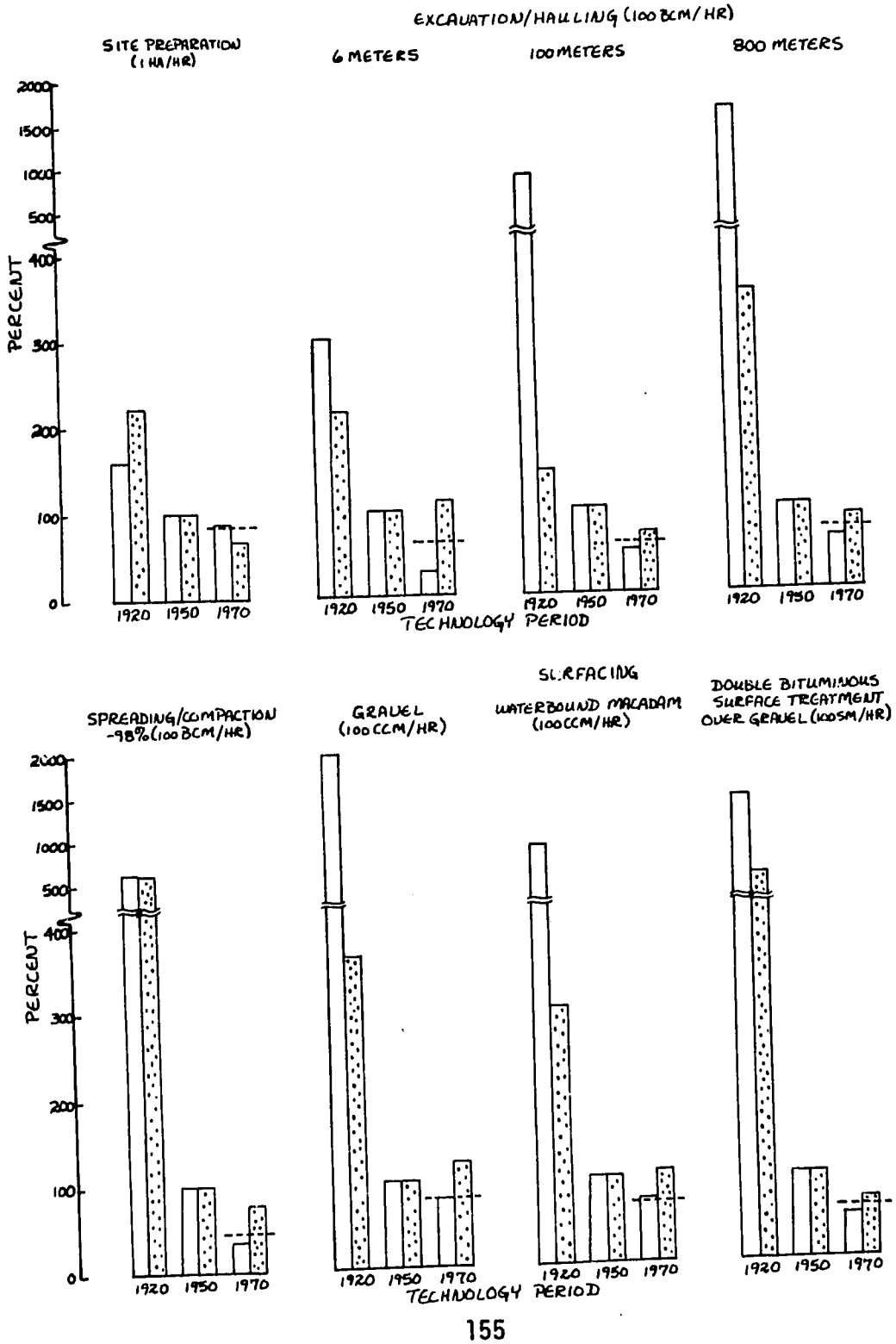
Note: □ Percent of 1920's labor, where labor is measured in unskilled men required for the given rate of production.

⊡ Percent of 1920's capital, where capital is measured in investment, in 1974 dollars, required for the given rate of production.

---- Indicates the level to which the quantities of labor and capital of the 1950's, relative to those of 1920's, fell due to efficiency; the further drop, generally of labor, below this line and rise, generally of capital, above it represents the changes due to bias (from Table 3.7).

Best-practice packages are those which appear as least-cost, or within 10 percent of it, at the prices of the period coincident with that of the technology; where more than one package is involved, the data for the various packages is averaged.

Figure 3.3b: Labor and capital requirements of the best-practice technical packages of each technology period as a percentage of those of the 1950's, for each stage of construction (source: Table B.6).



(Figure 3.3b continued)

Note: □ Percent of 1950's labor, where labor is measured in unskilled men required for the given rate of production.

▒ Percent of 1950's capital, where capital is measured in investment, in 1974 dollars, required for the given rate of production.

---- Indicates the level to which the quantities of labor and capital of the 1970's relative to those of the 1950's fell due to efficiency; the further drop, generally of labor, below this line and rise, generally of capital, above it represents the changes due to bias (from Table 3.7).

Best-practice packages are those which appear as least-cost, or within 10 percent of it, at the prices of the period coincident with that of the technology; where more than one package is involved, the data for the various packages is averaged.

Table 3.7: Distribution of the percentage change in the quantity of labor and capital required by the best-practice packages, for each stage of construction, in the 1920's to the 1950's and the 1950's to 1970's transitions (source: Tables B.5 and B.6 and Figure 3.3).

	Distribution of the Percentage Change							
	$100 \cdot (Resource_{50} - Resource_{20})/Resource_{20}$				$100 \cdot (Resource_{70} - Resource_{50})/Resource_{50}$			
Stage and Resource	Total[a]	Efficiency[b]	Bias[b]	Salter's Bias[b]	Total[a]	Efficiency[b]	Bias[b]	Salter's Bias[b]
Site Preparation								
Labor	-37.8	-36.2	-1.6	+7.23	-13.2	-14.9	+1.7	+3.01
Capital	-55.0	-36.2	-18.8	-20.4	-32.6	-14.9	+17.7	-19.4
Excavation/Hauling								
-6M Labor	-67.1	-54.3	-12.8	-19.3	-70.4	-38.2	-32.2	-144.
Capital	-53.4	-54.3	+0.9	+25.2	+12.0	-38.2	+50.2	+128.
-100M Labor	-88.2	-69.9	-18.3	-169.	-48.6	-41.8	-6.8	-22.6
Capital	-30.4	-69.9	+39.5	+197.	-28.5	-41.8	+13.3	+17.1
-800M Labor	-93.8	-85.1	-8.7	-166.	-40.8	-32.3	-8.5	-23.5
Capital	-71.6	-85.1	+13.5	+189.	-16.4	-32.3	+15.9	+17.9
Spreading/Compaction								
-98% Labor	-83.6	-75.7	-7.9	-0.607	-64.9	-55.3	-9.6	-42.8
Capital	-83.4	-75.7	-7.7	+1.30	-21.3	-55.3	+34.0	+81.5
Gravel Surfacing								
Labor	-94.9	-89.9	-5.0	-87.5	-20.0	-19.7	-0.3	-13.3
Capital	-72.5	-89.9	+17.4	+355.	+21.0	-19.7	+40.7	+37.2
Waterbound Macadam Surfacing								
Labor	-88.5	-78.9	-9.6	-41.3	-27.0	-29.2	+2.2	-11.1
Capital	-66.5	-78.9	+12.4	+149.	+5.0	-29.2	+34.2	+33.4
Double Bituminous Surface Treatment over Gravel								
Labor	-92.9	-88.7	-4.2	-46.3	-48.8	-41.5	-7.3	-9.55
Capital	-79.6	-88.7	+9.1	+143.	-31.5	-41.5	+10.0	+23.2

(Table 3.7 continued)

[a]From Figure 3.3.

[b]Equations for calculating these values are given and discussed in Section 2.31. Calculation of columns 2 and 6, efficiency, and columns 4 and 8, Salter's bias, are based on Salter's work, while columns 3 and 7 are the difference between the total percentage change from Figure 3.3 and that due to efficiency.

bias, in the transition from the 1920's to 1950's and in that from the 1950's to 1970's. It should be noted that Salter's measure of bias is an indication of what would happen, in terms, for example, of reducing labor and augmenting capital, if it could be done, and not of what actually happened; columns 3 and 7 of Table 3.7, then, combine the efficiency results with the data in Figure 3.3 to derive the actual percentage change in inputs due to bias.

This thus completes the presentation of the results of the stage-level analysis. Further discussion of these results and their implications, as well as some limited sensitivity testing of them, is left to Chapter 4.

3.2 Project Designs and Costs

Highway construction and use are not independent, making it important to extend the stage-level analysis to the project-level and to look at some alternative project designs as well as construction technologies. Differences among designs lie primarily in the quality of the final product and in the quantities of the various stages in the overall project. In the course of the stage-level analysis, meaningful comparisons could not be made among the various surfaces because the nature of the surface itself, both in terms of the material and in its level of compaction and general quality of construction (although the latter parameter is assumed constant), affects the quality of the final product. Somewhat similarly, the degree of compaction in the spreading/compaction stage potentially interacts with the other stages of construction in

terms of project quantities and/or affects the quality of the final product. Site preparation and excavation/hauling, on the other hand, have no impact on the quality of the final product, as a cubic meter of excavation/hauling is the same regardless of how it is done. Noteworthy in the case of excavation/hauling are the variety of possible haul distances, a condition which varies widely among projects, and the range of possible construction scenarios, in terms of line hauling and borrowing, which affects the quantity of site preparation as well as the set of haul distances. Maintenance and user costs over the life of the project for a particular traffic profile serve as a very convenient, and measurable, indicator of the quality of the final product. The data required for the project-level analysis thus consists of the construction quantities and least-cost technical packages (and thus unit costs from the stage-level analysis) at various technology and price periods, for the various stages of construction of a representative set of alternative projects; also needed are the maintenance and user costs associated with these projects.

3.21 Selection of Projects

In investigating the interaction of design and technology in highway construction and use, three groups of projects are of interest, as indicated in Table 3.8. Before proceeding, the numbering scheme of the projects might be mentioned. The L and H indicate the level of design standards, which will be discussed shortly; the first digit represents the surfacing materials, the second the subgrade strength and surface

Table 3.8: A list of the projects considered in the analysis and their basic characteristics.

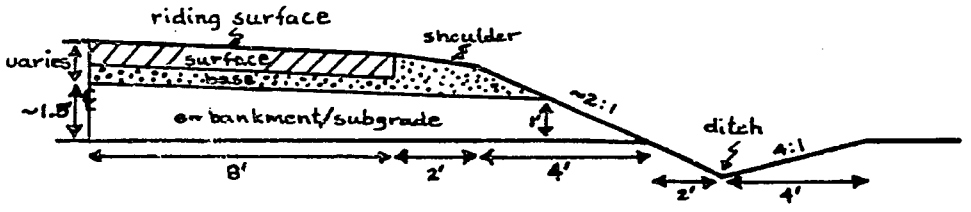
Project Number	Design Standards/ Initial Traffic (ADT)	Subbase/Base/ Surface Materials	Subgrade Strength (%CBR)/%CBR for which Surface Designed	Line Hauling/ Sideborrowing/ Pit Borrowing
L 114	low/80	-/-/gravel	7.0/7.0	short/-/near
L 214	low/80	-/gravel/wbm	7.0/7.0	short/-/near
L 314	low/80	-/gravel/dbst	7.0/7.0	short/-/near
H 215	high/400	-/gravel/wbm	7.0/7.0	long/-/near
H 315	high/400	-/gravel/dbst	7.0/7.0	long/-/near
H 415	high/400	gravel/wbm/dbst	7.0/7.0	long/-/near
L 314	low/80	-/gravel/dbst	7.0/7.0	short/-/near
L 324	low/80	-/gravel/dbst	3.5/3.5	short/-/near
L 334	low/80	-/gravel/dbst	3.5/7.0	short/-/near
H 315	high/400	-/gravel/dbst	7.0/7.0	long/-/near
H 325	high/400	-/gravel/dbst	3.5/3.5	long/-/near
H 335	high/400	-/gravel/dbst	3.5/7.0	long/-/near
L 311	low/80	-/gravel/dbst	7.0/7.0	short/ 1 side/-
L 314	low/80	-/gravel/dbst	7.0/7.0	short/-/near
L 315	low/80	-/gravel/dbst	7.0/7.0	long/-/near
H 312	high/400	-/gravel/dbst	7.0/7.0	short/2 sides/near
H 313	high/400	-/gravel/dbst	7.0/7.0	long/2 sides/near
H 315	high/400	-/gravel/dbst	7.0/7.0	long/-/near
L 316	low/80	-/gravel/dbst	7.0/7.0	short/-/far
L 317	low/80	-/gravel/dbst	7.0/7.0	long/-/far
H 317	high/400	-/gravel/dbst	7.0/7.0	long/-/far

(Table 3.8 continued)

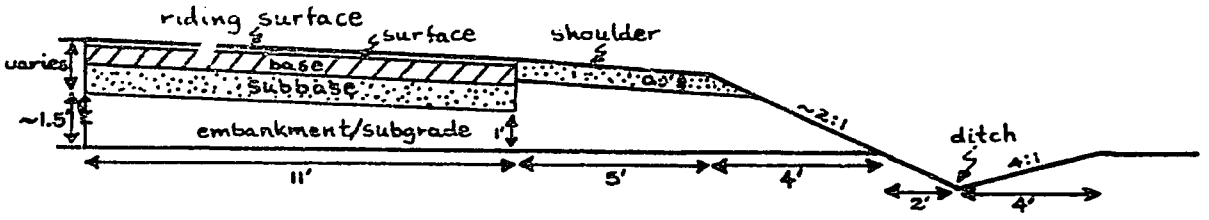
Note: Design standards and traffic profile details:

	Low Standard	High Standard
Design Speed	25 mph	60 mph
Maximum Grade	9 %	4 (some 6) %
Minimum Radius of Curvature	230 feet	1,300 feet
Minimum Length of Vertical Curves	400 feet	600 feet
Initial Traffic	80 ADT	400 ADT
Truck Percentage	20 %	30 %
Annual Growth Rate Over 15 Years	10 %	10 %

Low Standard Cross Section:



High Standard Cross Section:



design combination, and the third the excavation/hauling scenario. One numerical parameter is varied in each set of projects while the others are held constant, for the low and high standard design alternatives.

In the first group of projects, the surfacing material is allowed to vary, the surfaces being well-graded gravel (p L114), waterbound macadam with the gravel as a base (p L214, H215), double bituminous surface treatment with the gravel as a base (p L314, H315, and double bituminous surface treatment with the waterbound macadam as a base and the gravel as a subbase (p H415). As indicated in Section 3.12, these particular surfaces were selected because of their use in all three technology periods, being reasonably common as surfaces in the 1920's while more recently being used on relatively low volume, rural roads, and because of their flexibility in terms of being able to be constructed using alternative technical packages. Construction, maintenance, and user costs may be expected to vary among these projects.

In the second project group, the degree of compaction of the subgrade is allowed to vary and with it the design of the surface. Three combinations occur: (1) a 7 percent California Bearing Ratio* (CBR)

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*CBR is a measure of the strength of the subgrade and can be expressed as a function of the soil type, its density, and its moisture content, but as noted in Section 3.12 such data seems to be available for only a few materials, one being silty clay. A soaked CBR of 7 percent corresponds to compaction in the range of 95 to 100 percent of the standard AASHO compaction of silty clay within ± 2 percent of the optimum moisture content (i.e., the 98 percent compaction case), while a soaked CBR of 3.5 percent corresponds to 91 to 96 percent compaction of the same (i.e., the 93 percent compaction case) (116). It might further be noted that these are relatively low CBR values, resulting in the need for rather thick surfacing layers.

with a suitable surface thickness (p L314, H315); (2) a 3.5 percent CBR with a suitable surface thickness (p L324, H325); and (3) a 3.5 percent CBR with a surface thickness suitable for a 7 percent CBR (p L334, H335). A comparison of the first two cases yields insight into the trade-off in construction costs between the compacting and affected activities and the surfacing activities, while the maintenance and user costs may be expected to be the same. Comparison of the last case with each of the first two yields insight into the trade-off between construction costs now, in terms of the compacting and affected activities or the surfacing activities, and maintenance and user costs later.

In the third group of projects, the scenario for the excavation and hauling tasks is allowed to vary. It is assumed that all fill material for the embankment comes from cuts for the road (termed line haul) and from borrow areas. Assuming borrowing from alongside the road is possible, various scenarios arise: (1) short line haul with sideborrow on one side (p L311); (2) short line haul with sideborrow on both sides and near pit borrow as necessary (p H312); (3) long line haul with sideborrow on two sides and near pit borrow as necessary (p H313); (4) short line haul with near pit borrow (p L314); and (5) long line haul with near pit borrow (p L315, H315). Assuming borrowing can only be done at some distance from the road (e.g., 305 meters or 1000 feet) as is more common today, a couple scenarios arise: (1) short line haul with far pit borrow (p L316); and (2) long line haul with far pit

borrow (p L317, H317). Maintenance and user costs may be expected to be constant over these projects, with the trade-offs showing up in the construction costs.

Also varying in each of these project groups are the design standards and traffic. While it seemed desirable at the outset to use design standards commensurate with each technology period, this proved to be unfeasible due to a paucity of design data for the 1920's (about all that could be found were cross sections indicating road width and surface thickness); instead, it was decided to use today's designs for two-lane, low volume, rural roads. As it is desirable to actually build rather different roads for different design standards, rolling terrain with reasonably steep grades is selected, with the road crossing it in going from point A to point B. Two sets of design standards at reasonably opposite ends of the spectrum, as given in the note to Table 3.8, are defined with the help of such sources as the American Association of State Highway Officials (4), Oglesby and Altenhofen (59), and Vance (112). The low standard design has a 4.88 meter (16 foot) surface and two 0.61 meter (2 foot) shoulders, grades up to 9 percent, and a design speed of some 40 kilometers per hour (25 miles per hour); thus it essentially follows the contour of the land, with cuts and fills primarily resulting from the ditches and the 0.30 meter (1 foot) embankment, respectively. The high standard design, on the other hand, had a 6.71 meter (22 foot) surface and two 1.52 meter (5 foot) shoulders, grades up to 4 percent (a few up to 6 percent to avoid excessive cuts), and a design speed of

some 97 kilometers per hour (60 miles per hour); it cuts through the terrain with very large cuts and fills, resulting in some thirty-five times the cut and five times the fill quantities of the low standard design. In overall length, the two roads are about the same, being 17.0 kilometers (10.6 miles) and 16.6 kilometers (10.3 miles), respectively. In line with these two design standards and their various surfaces, two sets of traffic are specified; an initial average daily traffic (ADT) of 80 with 20 percent trucks is used for the low standard design, and one of 400 with 30 percent trucks for the high standard, each with a 10 percent annual growth rate over the 15 year life of the road (reaching 334 ADT and 1671 ADT, respectively).

3.22 Estimation of Project Quantities and Costs

It was observed in the introduction to Section 3.2 that one of the primary differences among projects is in the quantities of each stage in the overall project. For each project in Table 3.8, then, Table 3.9 presents the full set of quantities for each stage of construction, including the various haul distances, compaction percentages, and surfacing materials encountered in the analysis; sizeable differences are evident. The derivation of these quantities is briefly touched upon here, leaving the more complete discussion to Section C.1.

In the inital stages of development of the project-level analysis, an effort was made to find a simple, two-lane, rural road, crossing rolling terrain with a minimum of artificial influences affecting its alignment, which has been constructed and for which the plans, quantity estimates, and so forth were still available. This alone proved

Table 3.9: Quantities of each stage of construction for each project.

Project Number	Site Preparation (HA)	Excavation/Hauling[a] (100 BCM)								Spreading/ Compaction (100 BCM)		Surfacing		
		Ditch	6M	9M	60M	100M	165M	500M	800M	98%	93%	Gravel (100CCM)	Water-bound Macadam (100CCM)	Double Bituminous Surface Treatment (100SM)
L 114	28.7	94.8	S 392	-	L 37.5	-	-	P 577	-	710	-	333	-	-
L 214	28.7	94.8	S 392	-	L 37.5	-	-	P 577	-	710	-	207	126	-
L 314	28.7	94.8	S 392	-	L 37.5	-	-	P 577	-	710	-	339	-	829
H 215	35.9	92.5	-	S 3800	-	-	P 931	L 2460	-	3490	-	282	170	-
H 315	35.9	92.5	-	S 3800	-	-	P 931	L 2460	-	3490	-	452	-	1110
H 415	35.9	92.5	-	S 3800	-	-	P 931	L 2460	-	3490	-	282	170	1110
L 314	28.7	94.8	S 392	-	L 37.5	-	-	P 577	-	710	-	339	-	829
L 324	28.5	94.8	S 390	-	L 37.5	-	-	P 536	-	-	668	526	-	829
L 334	28.5	94.8	S 390	-	L 37.5	-	-	P 536	-	-	668	339	-	829
H 315	35.9	92.5	-	S 3800	-	-	P 931	L 2460	-	3490	-	452	-	1110
H 325	34.9	92.5	-	S 3780	-	-	P 728	L 2460	-	-	3280	634	-	1110
H 335	34.9	92.5	-	S 3780	-	-	P 728	L 2460	-	-	3280	452	-	1110
L 311	34.7	47.4	S 489	B 625	L 37.5	-	-	-	-	710	-	339	-	829
L 314	28.7	94.8	S 392	-	L 37.5	-	-	P 577	-	710	-	339	-	829
L 315	28.5	94.8	S 352	-	-	-	-	L 75.7 P 539	-	710	-	339	-	829
H 312	56.7	-	-	B 937 S 6240	L 330	-	P 2220	-	-	3490	-	452	-	1110
H 313	44.3	17.6	-	B 631 S 3930	-	P 375	-	L 2460	-	3490	-	452	-	1110
H 315	35.9	92.5	-	S 3800	-	-	P 931	L 2460	-	3490	-	452	-	1110
L 316	28.7	94.8	S 392	-	L 37.5	-	-	-	P 577	710	-	339	-	829
L 317	28.5	94.8	S 352	-	-	-	-	L 75.7	P 539	710	-	339	-	829
H 317	35.9	92.5	-	S 3800	-	-	-	L 2460 P 931	-	3490	-	452	-	1110

[a]For excavation/hauling - S = spoil
L = line haul
P = pit borrow
B = sideborrow

Best Available Document

to be nearly impossible. With the additional condition that it be a project where different design standards and alignments had been considered and worked up or where such was even possible, it quickly became unfeasible, and it was decided to start from scratch.

On a U.S. Geological Survey topographic map of some rolling terrain, two points about 16 kilometers (10 miles) apart are selected, and a few possible alignments for each of the two design standards are planned, assuming no intermediate controls such as townships and quarries. Upon reviewing the wide variety of methods available for estimating earthwork quantities, which range from very rough to very detailed, it is decided to use one of the intermediate methodologies, a modified version of the one point model, in view of the geological data available (the topographic map with 6.1 meter [20 foot] contours) and the data pertaining to the alignment required by the Highway Cost Model (HCM) for estimating maintenance and user costs and surface conditions. The one point model simply computes the area of the cross section at each station (spaced every 60 meters [200 feet] along the route) and uses the average end area technique to compute the volumes, requiring only the centerline height difference between the terrain and road profile; due to the rolling terrain condition, side slope is also taken into account in calculating cross-sectional areas and finally volumes of earthworks. For the purposes of the study at hand, the intermediate alignment, in terms of road length and earthwork quantities, for both the low and high standard designs is selected; the details of these alignments, as required by the HCM, are given in Section C.1,

along with further details pertaining to laying out the route and estimating the earthwork quantities.

Given the basic earthwork quantities in terms of cut and fill volumes* for the two design standards, the distribution of cut between fill and spoil and of fill between cut and borrow remains to be determined along with the haul distances. This requires knowledge of the excavation/hauling scenarios of interest. Rather than going to a method as sophisticated as mass-haul diagrams, it is decided to simply review the cut and fill volumes given at 60 meter (200 foot) intervals along each road with two line haul distances (60 meters [200 feet] and 500 meters [1640 feet]) in mind, estimating the percentages of cut which can go to fill. The remainder of the fill, then, must come from borrow, the actual haul distances varying with the assumption as to the type of borrow, side or near or far pit, and the quantity and distribution of the material involved. In the low standard case, for example, the remaining fill is reasonably distributed along the road and thus can all be sideborrowed. In the high standard case, however, the remaining fill is large in quantity and unevenly distributed, and thus it is assumed sideborrow would be done to a limited distance from the road and then near pit borrow would begin as needed. In the near pit borrow scenario, the low standard design is penalized by a long haul distance, because a certain minimum size pit is assumed,

*Cut for the low standard road is 17,100 bank cubic meters, while fill is 57,700 compacted cubic meters; for the high standard road, cut is 589,000 bank cubic meters, and fill is 283,000 compacted cubic meters.

as is required by some equipment and by common sense, making the haul along the road quite long. As for the quantity of spoil and its haul distance, the remaining cut and the top six inches on the roadbed including the ditches and on all borrow areas go to spoil, with the haul distance being a weighted average. In order to limit the full set of haul distances thus derived to a reasonable number and to leave an allowance for underestimating, some limited grouping and general rounding up is done, resulting in the set of distances given in Table 3.9. Section C.12 contains a fuller discussion of the derivation of these excavation/hauling estimates.

The volume of spreading/compaction is simply taken as the quantity of fill material, under the assumption that compaction is done only in fill areas. The factor for converting compacted to bank measure varies with the level of compaction, being 1.23 for 98 percent compaction and 1.16 for 93 percent compaction.

As in the case of topsoil removal which goes to spoil, the roadbed including the ditches and all borrow areas must be cleared of brush and trees. The quantity of site preparation thus consists of these areas plus an additional 1.5 meters (5 feet) on either side of the road and an additional 10 percent on the pits, as an allowance for brush encroachment and working space.

Gravel and waterbound macadam surfacing are measured in volumetric units as a function of the surface design in terms of layer thickness, the road cross section, and the length of the route; double bituminous surface treatment is measured in units of area as a function of

the road cross section and length. Gravel shoulders are assumed in all cases, with a thickness equivalent to that of the surfacing materials for the low standard road since the shoulders are so narrow, and a fixed thickness of 15.2 centimeters (6 inches) for the high standard route. Section C.12 contains the final set of equations used in these calculations.

The surface design requires knowledge of the traffic expected over the design life of the road, the strength of the subgrade (i.e., its CBR), and the layer coefficients of the materials being used, which serve as indicators of the structural support value of the materials in the overall surface. It was decided at the outset to use the Transport and Road Research Laboratory's (TRRL's) design procedure (79), rather than that of the American Association of State Highway and Transportation Officials (AASHTO) (3), as TRRL's surface deterioration models (80) are used in the HCM. This results in somewhat lower standard surfaces (i.e., thinner layers) than might be expected from an AASHTO-based design, which is probably not unreasonable for low volume, rural roads.

Actually only the thickness of the gravel layer has to be designed, as the waterbound macadam is assumed to be 15.2 centimeters (6 inches), since this represents standard design practice at the time of its use and even today, and the double bituminous surface treatment has a thickness determined primarily by the size of the crushed stone used instead of the amount, with 2.2 centimeters (7/8 inch) being a common thickness.

Given the traffic in terms of the cumulative number of standard axles (8200 kilogram [18 kip] loads) over the project life and the subgrade CBR, the gravel thicknesses are designed with the help of a chart provided by TRRL (79). For the two cases of the properly designed surface over a 3.5 percent CBR (p L324, H325), however, the modified structural number* is used to design the gravel layer, such that the properly designed roads with the 7 percent (p L314, H315) and 3.5 percent (p L324, H325) CBR's have the same modified structural number; this is done under the assumption that two such roads should behave the same, which is also the basis of TRRL's use of the modified structural number to determine paved road deterioration. As for layer coefficients for the various materials, figures are derived with the help

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*The structural number (SN) of a pavement is defined by an empirical relationship between the thicknesses and material coefficients of its various layers as follows:

$$SN = \sum_{i=1}^{n} a_i t_i$$

where n = number of layers
a_i = material coefficient of layer i
t_i = thickness of layer i (inches)

The modified structural number (SN') incorporates the subgrade strength in terms of CBR into the measure as follows:

$$SN' = SN + 3.51(\log_{10}CBR) - 0.85(\log_{10}CBR)^2 - 1.43$$

SN', then, is used as an index of the strength of the surface (3, 80).

of AASHTO (3), TRRL (80), and Yoder and Witczak (117), among others; these and the layer thicknesses are given in Section C.11, along with further details about the surface designs. Waterbound macadam presents some problems in that no deterioration model can be found for it; this is resolved by using a modified version of TRRL's model for double bituminous surface treated roads, as this seems reasonable in light of descriptions in the literature of the surface and of its behavior and maintenance.

Given the quantities of each stage in each project, what is still required for the derivation of the construction costs of the projects are the technical packages to be used, and thus their unit costs, from the stage-level analysis. It is assumed that each of the projects is only a small part of a much larger project, and thus no constraints are placed on the selection of technical packages in terms of their having to be used long enough to warrant their being brought to the site without incurring some penalty charge. The selection of technical packages is, therefore, largely stage and economic conditions specific and not really project specific. Table 3.10, then, gives the least-cost technical packages for each of the 1920's, 1950's, and 1970's technology periods as well as those over all technology periods at the prices of 1930, 1974, and developing countries. As in the stage-level analysis, packages within 10 percent of the least-cost one are also included, with the data being averaged as necessary for the analysis. Also, in the case of the 1930 and 1974 pricing periods, these are the

Table 3.10: Least-cost technical packages for each stage of construction, for each technology period alone and over all periods, at the prices of 1930, 1974, and developing countries (source: Tables 3.6 and B.5).

Stage	1930,1974 Prices[a]			Developing Countries Prices			
	1920's Technology	1950's Technology	1970's Technology	1920's Technology	1950's Technology	1970's Technology	All Technologies 1920/1950/1970
Site Preparation	21	31	31	11	31	31	11/-/-
Excavation/ Hauling[b]							
Ditch	5-4	11-0	14-0	5-4,4-3	11-0	14-0	5-4,4-3/-/-
6M-S	7-6	10-10,9-9	13-16	5-4,4-3	9-9	12-15,13-16	5-4,4-3/-/-
9M-B	7-6	10-10,9-9	13-16,12-15	5-4,4-3	9-9,10-10	12-15	5-4,4-3/-/-
-S	7-6	10-10,9-9	13-16,12-15	5-4,4-3	9-9,10-10	12-15	5-4,4-3/-/-
60M-L	7-6	7-7[4-4][c]	8-11	5-4[8-7]	7-7,9-9, 10-10[4-4]	8-11	5-4[8-7]/-/-
100M-P	7-6,9-7	7-7,4-4	8-11	8-7	7-7,4-4	8-11	8-7/-/-
165M-P	9-7	7-7,4-4	8-11	8-7	7-7,4-4	8-11	8-7/-/-
500M-P	10-8	4-4	8-11	8-7	4-4	8-11	8-7/-/-
-L	-[d]	7-7[4-4]	8-11	6-5[8-7]	7-7[4-4]	8-11	6-5[8-7]/-/-
800M-P	10-8	4-4	8-11	8-7	4-4	8-11	8-7/-/-
Spreading/ Compaction							
98%	32	44,34	41,31	21	44,43,34,33	41,31	21/-/-
93%	31[e]	-	-	21	-	-	21/-/-
Surfacing							
Gravel	22	42,32	31,41	21	32,42	31,41	21/-/-
Waterbound Macadam	211	412,312,212, 112,512	311,411, 111,211	211,111	412,312, 112,212	311,411,111	-/-/311,411,111
Double Bituminous Surface Treatment Over Gravel	1121	2122,1122,2112, 1112,2121,1121, 2111,1111	1112,1212, 1111,1211	1111	2122,1122, 2121,1121	1122,1121, 1222,1221	-/-/1122,1121,1222, 1221
Double Bituminous Surface Treatment Over Waterbound Macadam	1121	2122,1122,2112, 1112,2121,1121, 2111,1111	1112,1212, 1111,1211	1111	2122,1122, 2121,1121	1122,1222, 1121,1221	-/-/1122,1222,1121, 1221

(Table 3.10 continued)

Note: Unit costs for these packages are found in Table B.5; where more than one package falls in the least-cost set (including the least-cost package and those within 10 percent), the average cost of the packages is used.

[a]These are the least-cost technical packages at the prices of the period coincident with that of the technology, as were used in the stage-level analysis of best-practice packages. The 1970's least-cost set is also least-cost over all technology periods at these prices.

[b]For excavation/hauling - S = spoil
B = sideborrow
L = line haul
P = pit borrow

[c]The package within the square brackets is the least-cost package for the haul distance, but as it cannot be used in such a line hauling activity, the next least-cost, technically feasible package is used.

[d]The design standard affects package selection - low standard 7-6 [10-8]
high standard 60% 10-8, 40% 7-6

[e]Only two 1920's technical packages were developed for the 93% compaction case, tp 11 and tp 21, neither of which cost less at 1930 or 1974 prices than the least-cost 98% compaction package, tp 32. A new technical package, tp 31, was thus created, using the spreading technique of tp 32 (12 ft blade grader [403] and 76 hp tractor [632]) and the compacting technique of tp 21 (2.5 ton roller [501] and horse), at a cost of $4.52/100BCM at the prices of 1930; it could not compete with tp 32 at the prices of 1974, however, so there is no 93% compaction considered for that price period.

least-cost technical packages at the prices of the period coincident with that of the technology, as were used in stage-level analyses of the best-practice packages.

Only a couple of situations arise in which the project can be said to influence the choice of technical packages. One involves the elevating grader (1920 tp 8-7; 1950 tp 4-4) which cannot be used for line haul or hauls under 60 meters (200 feet) or so; the second involves the use of a power shovel (1920 tp 10-8) in line haul, which is impossible in the low standard case due to the generally shallow depth of the cuts, but which is possible for an estimated 60 percent of the line haul work in the high standard case. In each of these cases, the next least-cost, technically feasible technical package is used, and that which could not be used is indicated in square brackets.

In order to complete the construction costs and bring them more in line with the maintenance and user costs, overhead and profit is included at 20 percent of total direct costs (i.e., labor, capital, and materials) (7, 28, 92). Minor structures are still left out, however, as they represent such a small share of total costs, and it is assumed that no major structures are necessary.

As for the quality of the final product, maintenance and user costs over the life of the project are used. As discussed in Section 2.22, the HCM is one of the models which investigates trade-offs among construction, maintenance, and user costs of alternative designs, with the construction technology being implicit in the rather aggregate cost data used in the analysis. Since it integrates many of the

existing methodologies of evaluating alternative designs in terms of the three costs, it seems an appropriate tool to use in deriving maintenance and user costs, although its data requirements are quite substantial. The majority of its requirements in terms of road characteristics, such as alignment, cross section, and surface design, and traffic profile are indicated throughout the discussion above; what remains consists of maintenance policies and unit costs and vehicle characteristics, costs, and utilization. Before proceeding, it should be noted that today's maintenance policies and technologies and vehicle transport technologies are assumed, although significant changes have occurred over time; maintenance itself is still often a relatively labor-intensive activity and has considerable potential for labor-capital substitution, presenting yet another interesting area for research. Furthermore, it is important to bear in mind that the final maintenance and user costs are simply intended as reasonable indicators, not absolute measures, of the quality of the final product; the degree of accuracy and detail desired in this phase is, therefore, much less stringent than that in the construction phase, the primary focus of the research.

With regard to maintenance policies, the personnel associated with the HCM served as a primary source of information based on their experience in applying the model; Harger (31) also proved to be useful in the particular case of waterbound macadam surfacing. Maintenance policies had to be developed and tested, using the HCM, for each subgrade/surface combination, the objective being to minimize maintenance and user costs

and to end up with all of the roads in reasonably poor condition at the end of 15 years, the assumed design life, such that their salvage values would be low and reasonably comparable so as to justify their being ignored. It was quickly learned that the two sets of properly designed roads on different subgrade CBR's (p L314 and L324; p H315 and H325) exhibited the same behavior, and thus have the same maintenance and user costs, so the two on the poor subgrade (p L324, H325) were eliminated from further testing. The high standard design generally requires more maintenance than the low due to its traffic volume, while the improperly designed roads on the 3.5 percent CBR's (p L334, H335), not surprisingly, require more still. The final set of maintenance policies is given and discussed in Section C.21.

Unit costs of each maintenance activity in the various policies is also needed. With the help of such sources as maintenance studies (34, 35), studies of alternative design standards (36, 59), and engineering texts (31), one or more sets of productivity data, generally in a crew format with materials requirements specified as well, are found for each maintenance activity. These are then priced at 1974, using equipment rental rates (54, 113), along with the labor and materials costs used in the construction phase of the study. Using the FHWA highway maintenance and operation cost index (68, 102), these prices can be indexed back to 1930. An indexing factor is also derived for developing conditions, on the basis of the relative trends exhibited in the stage-level construction costs and a comparison of Ethiopian (55) and U.S. maintenance

costs. Table C.2 contains the full set of maintenance unit costs.

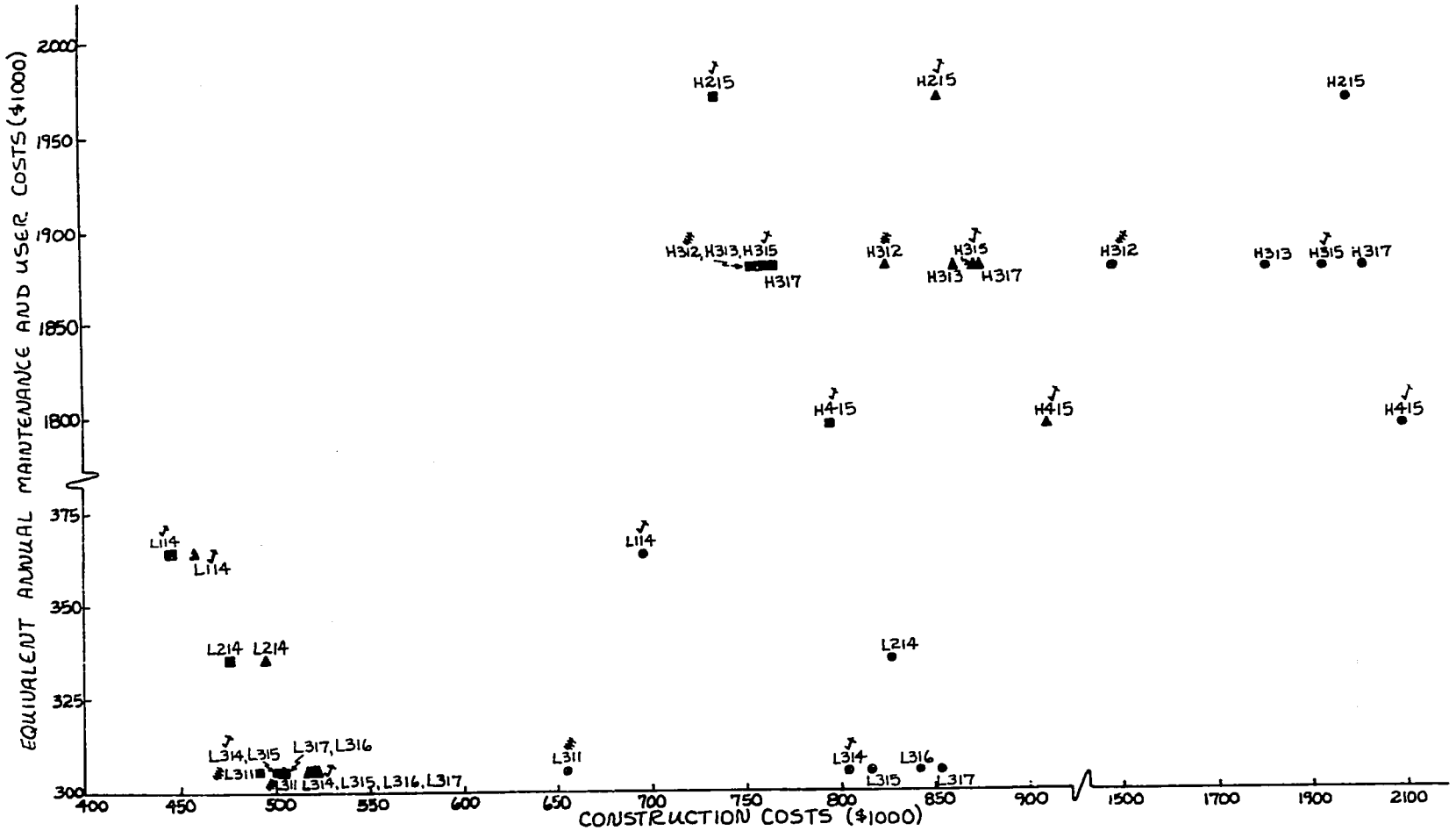
Vehicle characteristics, costs, and utilization constitute the final set of data needed for the project-level analysis. As in the case of maintenance policies, one set of vehicle characteristics and utilization data is used, although costs are required for all price periods. Four vehicle types, a car, a single-unit truck, and two semi-trailer combinations, are selected on the basis of their representativeness of the range of vehicles and the availability of data. The basic data required consists, for example, of fuel type, brake horsepower, maximum load, annual utilization in hours, and normal life in years; cost data is needed for such items as tires, insurance, registration, maintenance labor, and drivers. The primary sources for this data include Winfrey (115), Anderson, et al (61), Claffey (60), U.S. Federal Highway Administration (99), U.S. Bureau of Labor Statistics (94), and U.S. Interstate Commerce Commission (106). By and large, the 1974 cost data is readily available from these sources, although the U.S. Bureau of Labor Statistics labor wage and wholesale price indexes (91) are occasionally needed to update items. Since the HCM does not consider congestion or accidents, these items are ignored, as are overhead costs and value of time savings due to a lack of data. Unit costs at 1930 are generally 1974 prices indexed back with various sections of the U.S. Bureau of Labor Statistics wholesale and consumer price indexes (90, 91), except for labor costs which are handled more directly by means of a U.S. Bureau of Labor Statistics bulletin (95). As for developing countries' prices, vehicle cost figures are developed

in line with the set of economic conditions used in the construction cost phase, keeping in mind the vehicle information that is available in a few developing country case studies (10, 55, 62, 64). Fur further details on the vehicle characteristics, utilization, and cost data used in the analysis, see Section C.22.

3.23 Alternative Projects and Their Costs

Combining the project quantities with the unit costs of the least-cost technical packages for various technology and price periods and the various maintenance and user cost data via the HCM for the appropriate price periods yields the project-level results, as given in Table C.5, for each project under various technology and price conditions. As an initial step in the analysis of the interaction of design and technology in highway construction and use, Figure 3.4 presents a graphical representation of some of these results. For each project and each technology period, the maintenance and user costs incurred over the life of the project, expressed in terms of equivalent annual costs, are plotted against the construction costs. As these are value rather than quantity-based measures, various economic conditions need to be considered; 1974 and 1930 costs are used to represent U.S. conditions over the period of interest, while developing conditions are used to broaden the analysis and to indicate the sensitivity of the results to economic conditions. In developing equivalent annual maintenance and user costs, a discount rate is required; with the help of the Federal Reserve Bulletin (26), one which is roughly representative of the rate at which long-term bonds are floated is estimated for the three price conditions.

Figure 3.4a: Construction costs and lifetime maintenance and user costs, expressed in equivalent annual cost terms, of each project/technology combination at each design standard/traffic volume, for all project groups and all technology periods, at the prices of 1974 (source: Table C.5).

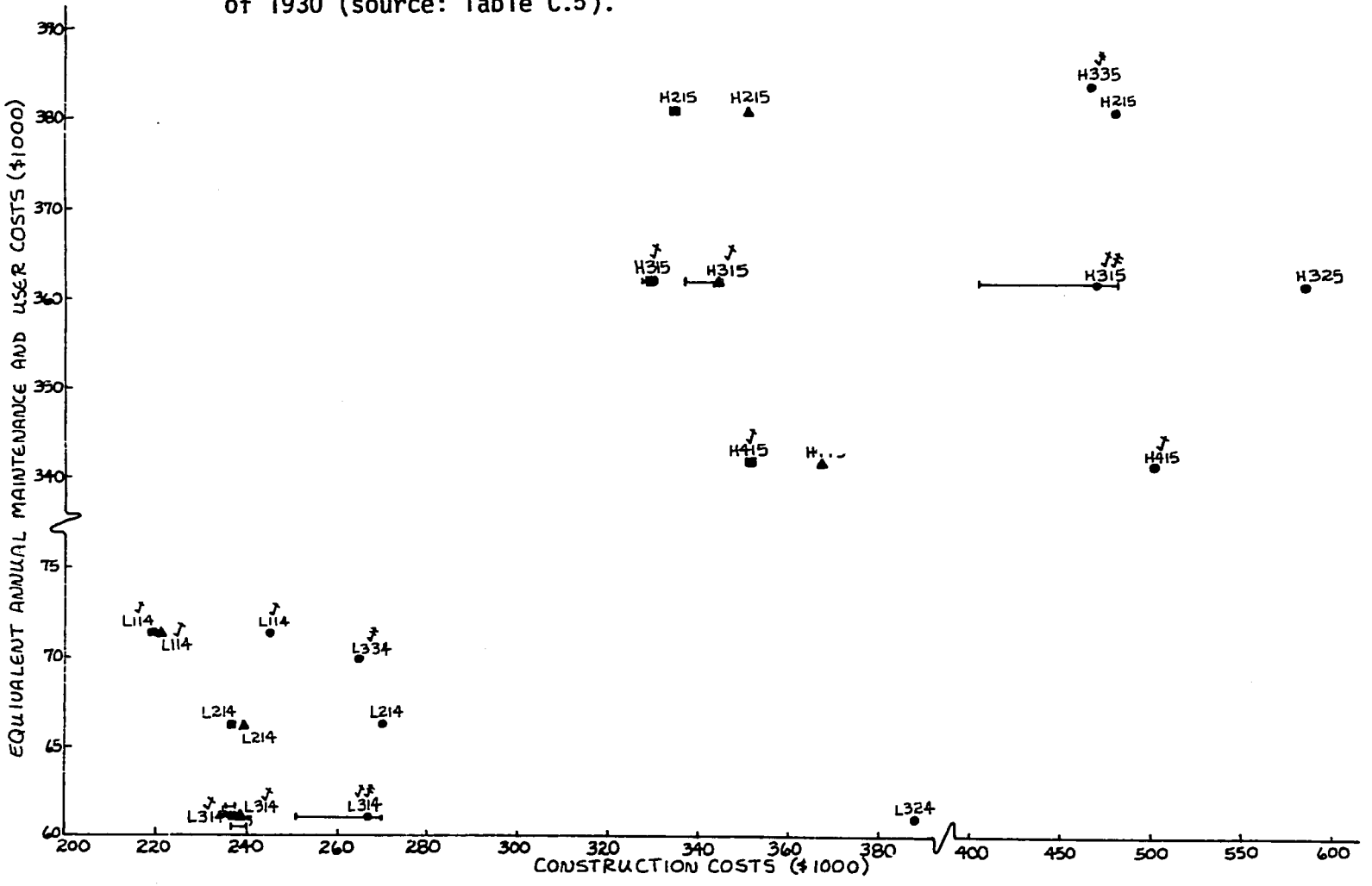


(Figure 3.4a continued)

<u>Note</u>: Technology periods: ● 1920, ▲ 1950, ■ 1970.

✓ Indicates an efficient project alternative, for a particular project group (✗ surface materials; ✗ excavation/hauling scenarios), design standard, and technology period.

Figure 3.4b: Construction costs and lifetime maintenance and user costs, expressed in equivalent annual cost terms, of each project/technology combination at each design standard/traffic volume, for all project groups and all technology periods, at the prices of 1930 (source: Table C.5).



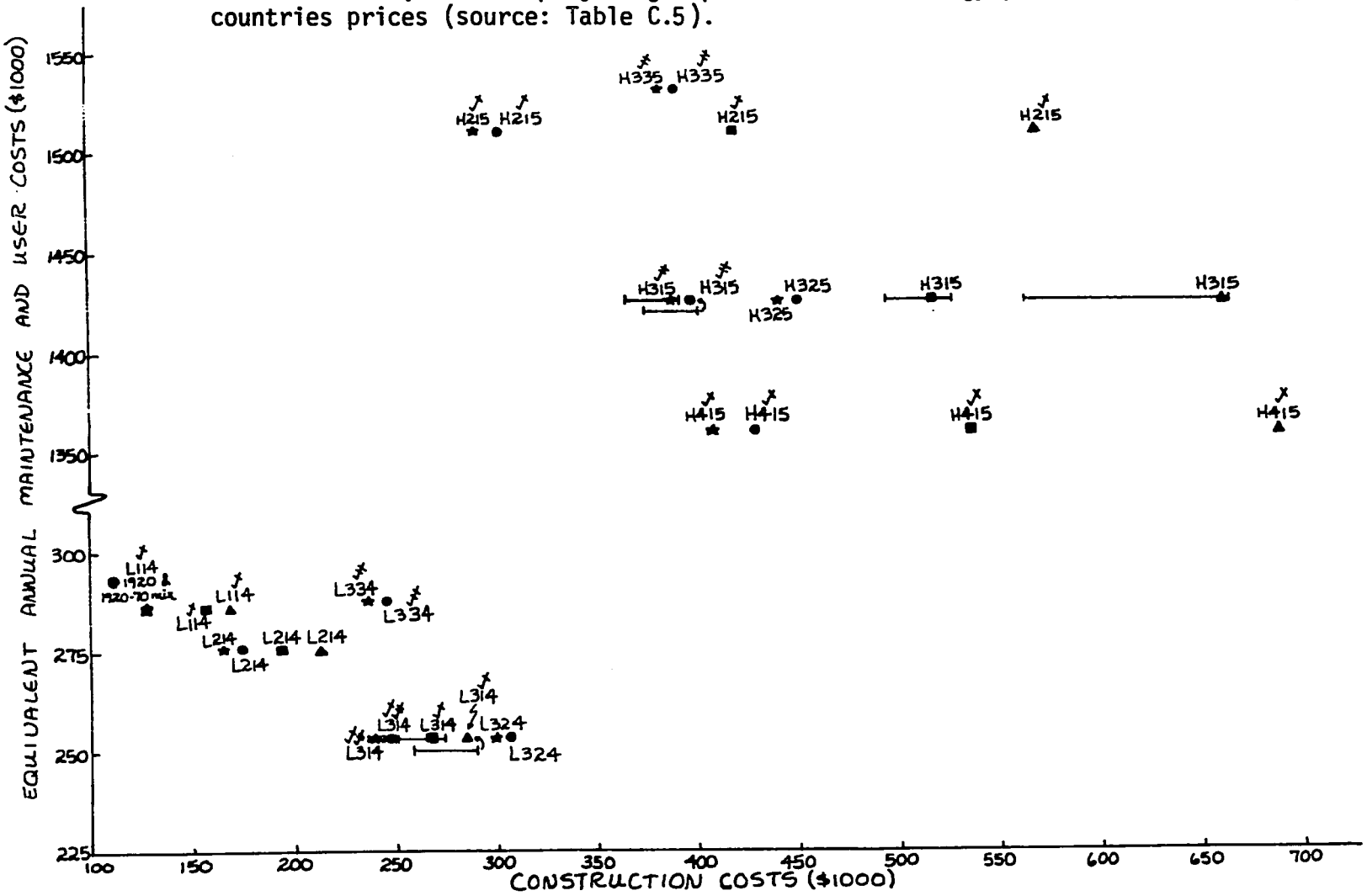
(Figure 3.4b continued)

Note: Technology periods: ● 1920, ▲ 1950, ■ 1970.

✓ Indicates an efficient project alternative, for a particular project group (✗ surface materials; ✗ subgrade strength/surface design), design standard, and technology period.

⊢—⊣ Indicates the range of construction costs of the alternative excavation/hauling scenarios, for a particular design standard and technology period.

Figure 3.4c: Construction costs and lifetime maintenance and user costs, expressed in equivalent annual cost terms, of each project/technology combination at each design standard/traffic volume, for all project groups and all technology periods, at developing countries prices (source: Table C.5).



(Figure 3.4c continued)

<u>Note</u>: Technology periods: ● 1920, ▲ 1950, ■ 1970, ★ 1920-70 mix.

✓ Indicates an efficient project alternative, for a particular project group (✓* surface materials; ✓** subgrade strength/surface design), design standard, and technology period.

⊢—⊣ Indicates the range of construction costs of the alternative excavation/hauling scenarios, for a particular design standard and technology period.

In the developing conditions case (Figure 3.4c), four technologies are indicated, where the fourth is a combination of the least-cost technical packages of all three technology periods (only the 1920's and 1970's actually contribute to the set [see Table 3.10]), and is thus the overall least-cost set of packages for developing conditions. In the 1974 and 1930 cases (Figures 3.4a and 3.4b, respectively), the 1970's technical packages are least-cost over those of all technology periods. It might also be observed that the alternative subgrade strength/surface design projects (p L314, L324, L334, H315, H325, H335) appear only at 1930 and developing prices, since at 1974 prices the least-cost 1920's technical package which compacts to 98 percent (tp 32) is actually less costly than is the package which compacts to only 93 percent (tp 31*); the difference between the 1930 and 1974 cases likely arises as a result of the relative capital intensities of the two packages. Finally, maintenance and user costs do not vary over the various excavation/hauling scenarios at a single design standard (p L311, L314, L315, L316, L317 and p H312, H313, H315, H317), and thus in the 1930 and developing cases, only the range of construction costs of these projects is given at the appropriate maintenance and user cost level. Such a pictorial representation as these graphs is useful in terms of developing a general feeling of how the technologies and designs interact in the various project groups. Moreover, these graphs are in essence production isoquants, depicting the trade-off

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*See footnote to Table 3.10.

between current and future expenditures in highway construction and use resulting from the design and technology mix; check marks by the project numbers indicate those combinations which are efficient in each group of projects at each design standard, for each technology period and over all periods.

Somewhat in line with the stage-level analysis, the next step consists of narrowing the sets of efficient projects to the least-cost sets under various price conditions. In order to further investigate the trade-offs among the various components of total project costs, the least-cost projects are thus identified for each of several cost items as appropriate; these include: (1) partial construction costs, which include only the cost of labor and capital used in construction, although site preparation materials (amounting to, at most, 4 percent of this cost item) are also included in the few cases where the site preparation packages use them; (2) total construction costs, including the cost of labor, capital, materials, and overhead and profit for all stages of construction except minor and major structures; (3) maintenance costs incurred over the life of the project, expressed in net present value terms using the same discount rate as above; (4) user costs incurred over the life of the project, similarly expressed; and (5) total project costs, the sum of the last three items. The results of this analysis for each project group and design standard are presented in Table 3.11 for the various price and technology periods; as previously, least-cost is defined as including all projects within 10 percent of the least-cost one.

Table 3.11a: Least-cost projects at each design standard from among the surface materials alternatives, under various technology and price conditions, for the various cost components (source: Table C.5).

Design Standard/ Price Period/ Technology Period	Construction Costs		Operation Costs[b]		Total Project Costs[b]
	Partial[a]	Total	Maintenance	User	
Low Standard Design					
1930 Prices					
1920	L114	L114,L314,L214	L314	L314,L214	L314,L214,L114
1950	L114	L114,L314,L214	L314	L314,L214	L314,L214
1970	L114,L314	L114,L214,L314	L314	L314,L214	L314,L214
overall[c]	L114,L314 @ 1970	L114,L214,L314 @ 1970,50	-	-	L314,L214 @ 1970,50,20
1974 Prices					
1920	L114	L114	L314	L314,L214	L314,L214
1950	L114	L114,L214	L314	L314,L214	L314,L214
1970	L114,L314	L114,L214	L314	L314,L214	L314,L214
overall[c]	L114,L314 @ 1970	L114 @ 1970,50 L214 @ 1970	-	-	L314@1970,50,20 L214@1970,50
Developing Prices					
1920	L114	L114	L314	L314,L214	L314,L214,L114
1950	L114,L314	L114	L314	L314,L214	L314,L214,L114
1970	L114,L314	L114	L314	L314,L214	L314,L214,L114
1920-70 mix	L114	L114	L314	L314,L214	L314,L214,L114
overall[c]	L114@mix,1920	L114@mix,1920	-	-	L314,L214,L114 @mix,1920,70,50

(Table 3.11a continued)

Design Standard/ Price Period/ Technology Period/	Construction Costs		Operation Costs[b]		Total Project Costs[b]
	Partial[a]	Total	Maintenance	User	
High Standard Design					
1930 Prices					
1920	H315,H215,H415	H315,H215,H415	H415	H415,H315,H215	H415,H315,H215
1950	H315,H215	H315,H215,H415	H415	H415,H315,H215	H415,H315,H215
1970	H315	H315,H215,H415	H415	H415,H315,H215	H415,H315,H215
overall[c]	H315 @ 1970	H315,H215 @ 1970,50 H415 @ 1970	-	-	H415,H315 @ 1970,50,20 H215 @ 1970,50
1974 Prices					
1920	H315,H215,H415	H315,H215,H415	H415	H415,H315,H215	H415,H315,H215
1950	H315,H215	H215,H315,H415	H415	H415,H315,H215	H415,H315,H215
1970	H315	H215,H315,H415	H415	H415,H315,H215	H415,H315,H215
overall[c]	H315 @ 1970	H215,H315,H415 @ 1970	-	-	H415 @ 1970,50,20 H315,H215 @ 1970,50
Developing Prices					
1920	H315	H215	H415	H415,H315,H215	H415,H315,H215
1950	H315,H215,H415	H215	H415	H415,H315,H215	H415,H315,H215
1970	H315,H215,H415	H215	H415	H415,H315,H215	H415,H315,H215
1920-70 mix	H315	H215	H415	H415,H315,H215	H415,H315,H215
overall[c]	H315 @ mix,1920	H215 @ mix,1920	-	-	H415,H315 @ mix, 1920,70,50 H215 @ mix,1920

(Table 3.11a continued)

Note: Least-cost includes those projects within 10 percent of the least-cost project, the order of the listing being from the lowest to highest in cost.

[a]Include cost of labor and capital used in construction, although site preparation materials ($\leq$ 4% of this cost item) are also included in the few cases where they are used.

[b]Expressed in net present value terms, the discount rate varying with the price period.

[c]Looking across all technology periods, for a particular price period and cost component, this is the least-cost set of project/technology combinations.

Table 3.11b: Least-cost projects at each design standard from among the subgrade strength/surface design alternatives, under various technology and price conditions, for the various cost components (source: Table C.5).

Design Standard/ Price Period/ Technology Period	Construction Costs		Operation Costs[b]		Total Project Costs[b]
	Partial[a]	Total	Maintenance	User	
Low Standard Design					
1930 Prices					
1920	L334,L314,L324	L334,L314	L314,L324	L314,L324,L334	L314,L334
Developing Prices					
1920	L334,L324,L314	L334,L314	L314,L324	L314,L324,L334	L314,L324
1920-70 mix	L334,L324,L314	L334,L314	L314,L324	L314,L324,L334	L314,L324
overall[c]	L334,L324,L314 @ mix	L334,L314 @mix,1920	-	-	L314,L324 @ mix, 1920
High Standard Design					
1930 Prices					
1920	H335,H325,H315	H335 H315	H315,H325	H315,H325,H335	H315,H325,H335
Developing Prices					
1920	H335,H325,H315	H335,H315	H315,H325	H315,H325,H335	H315,H325,H335
1920-70 mix	H335,H325,H315	H335,H315	H315,H325	H315,H325,H335	H315,H325,H335
overall[c]	H335 @mix,1920 H325,H315 @ mix	H335,H315 @mix,1920	-	-	H315,H325,H335 @ mix, 1920

Note: See note and footnotes in Table 3.11a. The 93% compaction case (i.e., CBR of 3.5%) is only considered for the horse-drawn roller in the 1920's, as the powered rollers are able to achieve 98% compaction (i.e., CBR of 7.0%) with relative ease; at the prices of 1974 the horse-drawn roller, even at 93% compaction, cannot compete in unit cost terms with the powered roller at 98% compaction.

Table 3.11c: Least-cost projects at each design standard from among the alternative excavation/hauling scenarios, under various technology and price conditions, for the various cost components (source: Table C.5).

Design Standard/ Price Period/ Technology Period	Construction Costs		Total Project Costs[b]
	Partial[a]	Total	
Low Standard Design			
1930 Prices			
1920	L311	L311,L314,L315,L316,L317	L311,L314,L315,L316,L317
1950	L311	L311,L314,L315,L316,L317	L311,L314,L315,L316,L317
1970	L311	L311,L314,L315,L317,L316	L311,L314,L315,L317,L316
overall[c]	L311 @ 1970	L311 @ 1970,50,20 L314,L315,L317,L316 @ 1970,50	L311,L314,L315,L317,L316 @ 1970,50,20
1974 Prices			
1920	L311	L311	L311,L314,L315,L316,L317
1950	L311	L311,L314,L315,L316,L317	L311,L314,L315,L316,L317
1970	L311	L311,L314,L315,L317,L316	L311,L314,L315,L317,L316
overall[c]	L311 @ 1970	L311,L314,L315,L317,L316 @ 1970,50	L311,L314,L315@1970,50,20 L317,L316 @ 1970,50
Developing Prices			
1920	L311,L314,L315	L311,L314,L315,L316,L317	L311,L314,L315,L316,L317
1950	L311	L311,L314	L311,L314,L315,L316,L317
1970	L311	L311,L314,L315,L317,L316	L311,L314,L315,L317,L316
1920-70 mix	L311,L314	L311,L314,L315,L316,L317	L311,L314,L315,L316,L317
overall[c]	L311,L314 @ mix	L311 @ mix,1920,70,50 L314,L315,L316,L317 @ mix,1920	L311,L314,L315,L316,L317 @ mix,1920,70,50

(Table 3.11c continued)

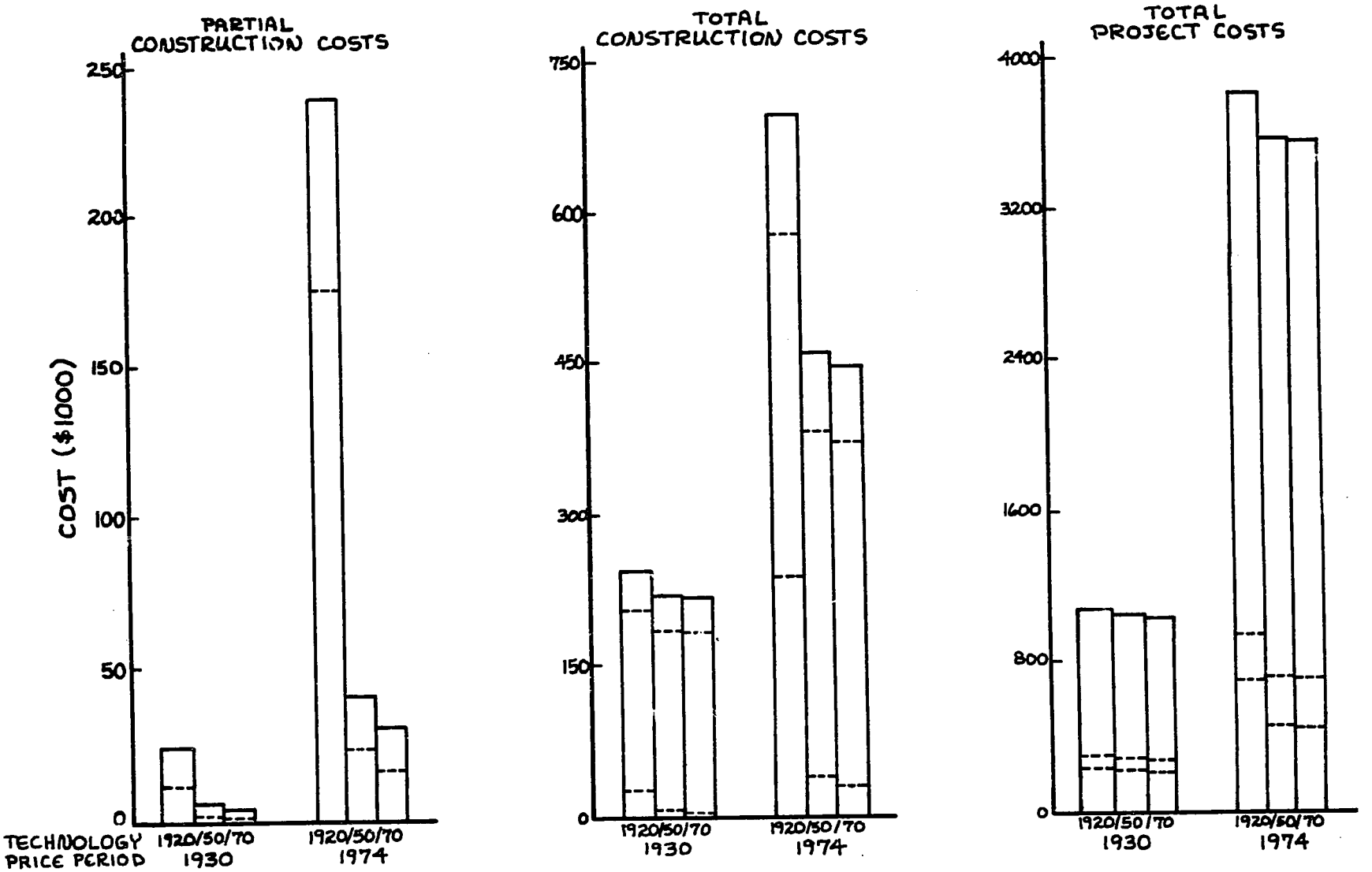
Design Standard/ Price Period/ Technology Period	Construction Costs		Total Project Costs[b]
	Partial[a]	Total	
High Standard Design			
1930 Prices			
1920	H312	H312	H312,H313,H315,H317
1950	H312	H312,H313,H315,H317	H312,H313,H315,H317
1970	H312,H313,H315	H312,H313,H315,H317	H312,H313,H315,H317
overall[c]	H312,H313,H315 @ 1970	H312,H313,H315,H317 @ 1970,50	H312,H313,H315,H317 @ 1970,50,20
1974 Prices			
1920	H312	H312	H312,H313,H315,H317
1950	H312	H312,H313,H315,H317	H312,H313,H315,H317
1970	H312,H313,H315,H317	H312,H313,H315,H317	H312,H313,H315,H317
overall[c]	H312,H313,H315, H317 @ 1970	H312 @ 1970,50 H313,H315,H317 @ 1970	H312,H313,H315,H317 @ 1970,50,20
Developing Prices			
1920	H312	H312,H315,H313,H317	H312,H315,H313,H317
1950	H312	H312	H312,H313,H315,H317
1970	H312,H313	H312,H313,H315,H317	H312,H313,H315,H317
1920-70 mix	H312	H312,H315,H313,H317	H312,H315,H313,H317
overall[c]	H312 @ mix	H312,H315,H313,H317 @ mix, 1920	H312,H315,H313,H317 @ mix, 1920,70,50

Note: See note and footnotes in Table 3.11a. Variation of the excavation/hauling scenario affects only construction costs; maintenance and user costs are thus not included separately in the table, as they are the same across all projects at a particular design standard.

Figure 3.5 is presented to give some indication of the relative magnitudes of these various cost items for a couple of projects under various price and technology conditions over time in the U.S. For a low standard, gravel surfaced road (p L114) and a high standard, double bituminous surface treated road (p H315), then, the partial construction, total construction, and total project costs are plotted with their various component parts indicated. The construction cost items vary with the technology and price period, while all other costs vary only with the price period. It might also be noted that, much as in Figure 3.2 in the stage-level analysis, this figure indicates the transition in costs that actually occurred, as well as that which would have occurred had construction technology not changed as it did, although in this case maintenance and transport technology are still assumed constant at the level of today. It should also be remembered that partial construction costs represent only best-practice technical packages, accounting in part for their rather small share of total construction costs.

This completes the presentation of the project-level results; further discussion of these results and their implications, as well as the limitations of the analysis, is taken up in Chapter 4.

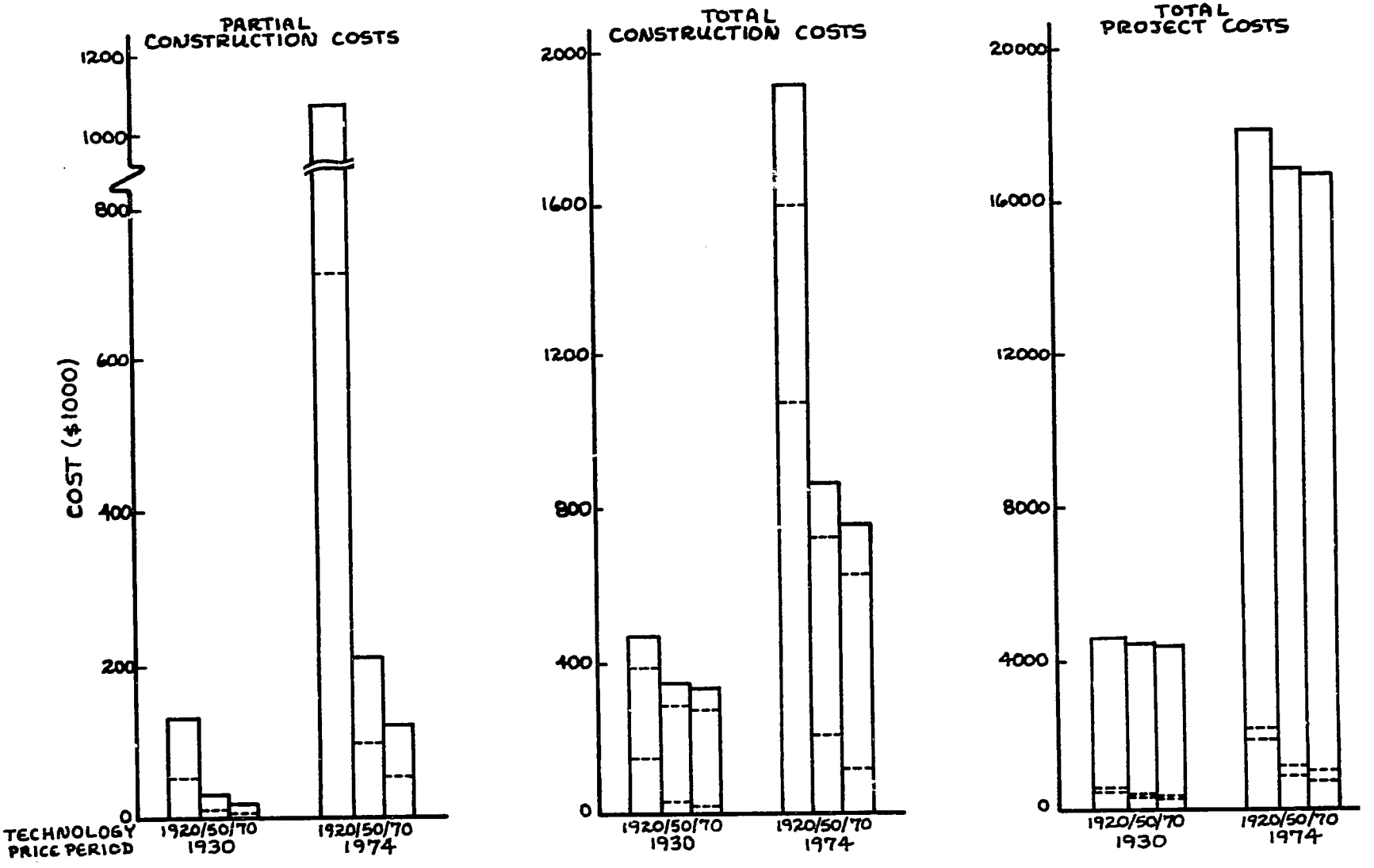
Figure 3.5a: Various components of project costs for a low standard, gravel road (p L114), under various technology and price conditions (source: Table C.5).



(Figure 3.5a continued)

<u>Note</u>:	Partial construction costs:	The lower portion of the bar chart represents the cost of labor and the upper portion that of capital, although site preparation materials ($\leq$ 4% of partial construction costs) are also included here in the few cases (1970's technology) where they are used.
	Total construction costs:	The lower portion of the bar chart represents the cost of labor and capital, the middle portion that of materials, and the upper portion that of overhead and profit.
	Total project costs:	The lower portion of the bar chart represents the total cost of construction, while the middle and upper portions respectively represent the maintenance and user costs incurred over the life of the project; these two latter costs are expressed in net present value terms, the discount rate varying with the price period.

Figure 3.5b: Various components of project costs for a high standard, double bituminous surface treated road on a gravel base (p H315), under various technology and price conditions (source: Table C.5).



Note: See note in Figure 3.5a.

CHAPTER 4

DISCUSSION OF THE RESULTS

In much the same way that Chapter 3 presents the results, this chapter discusses them, devoting one section to the stage and one to the project-level analysis. Section 4.1 focuses on the change in highway construction technology over time and its implications for the future; in the course of the discussion, changes in the nature of the technical packages, the various sets of efficient technical packages, and the role of efficiency and substitution in technology change are considered and evaluated. Section 4.2 then focuses on the interaction of design and technology in highway construction and use; projects involving various surfacing materials, subgrade strengths, and methods of borrowing earthwork materials are considered and compared within their respective groups, accompanied by a discussion of the limitations of the analysis and implications of the results.

4.1 Change in Highway Construction Technology Over Time

In the analysis of technology change in highway construction, the first logical step is a qualitative investigation of how the technical packages, in terms of the resources constituting them, have changed (see Table 3.1 and Figure 3.1; Tables B.1 and B.2 might also be helpful). In the 1920's, small capacity, unpowered equipment operated largely by unskilled laborers with horses or mules as a source of power and a few skilled men acting in a supervisory role is most common, while in the

1950's the use of much larger capacity, powered equipment operated largely by skilled laborers with occasional unskilled assistants is the rule. The transition to the 1970's is not so great, primarily involving the introduction of still more powerful, larger capacity equipment as well as a few new types.

Both relatively labor-intensive (tp 11) and capital-intensive (tp 21, 31) technical packages exist for site preparation in all periods. Information on site preparation for highways is sparse, however, necessitating some limited use of data pertaining to building construction and road maintenance, particularly for the labor-intensive packages in the 1950's and 1970's; this perhaps, in part at least, explains their poor performance relative to that of the 1920's. As for the capital-intensive packages, that of the 1920's is replaced by larger bulldozers and/or additional items of equipment in the 1950's and 1970's, with significant decreases in investment and relatively small, if any, decreases in labor.

The progression of technology is well demonstrated by the technical packages for excavation/hauling, the stage of construction which seems to have received the most attention in the literature. The technical packages of the 1920's represent a broad range of capital/labor ratios, from the highly labor-intensive handtools (tp 1-1, 1-2, 2-1, 2-2, 3-1, 3-2) through the horse-drawn scrapers (tp 4-3, 5-4, 6-5) and the horse or tractor-drawn elevating graders (tp 8-7, 9-7) to the highly capital-intensive bulldozers (tp 7-6) and power shovels (tp 10-7, 10-8, 10-9). In the 1950's and 1970's the span of capital/labor ratios is practically

reduced to a single value, with the 1970's generally being somewhat more capital-intensive than the 1950's. The 0.2 to 0.5 cubic yard, horse-drawn scrapers (tp 4-3, 5-4, 6-5) of the 1920's are replaced by 6 to 15 cubic yard, power-driven scrapers (tp 5-5, 6-6, 7-7) in the 1950's, with a significant decrease in labor and some to no increase in investment (with increasing haul distance); 20 to 30 cubic yard scrapers (tp 9-12, 10-13) and 11.5 to 21.5 cubic yard elevating scrapers (tp 7-10, 8-11) take over in the 1970's, with decreases in both labor and investment. With a significant decrease in labor and a slight increase to a decrease in investment (with increasing haul distance), the larger 1950's elevating graders (tp 4-2, 4-4) replace those (tp 8-7, 9-7) of the 1920's; in the 1970's 1.75 to 5 cubic yard front end loaders (tp 4-1, 4-2, 4-7, 5-3, 5-5, 5-8, 6-4, 6-6, 6-9) come into being. Finally, the 60 horsepower bulldozer (tp 7-6) and 0.75 cubic yard power shovel (tp 10-7, 10-8, 10-9) of the 1920's are replaced by successively largerpieces in the 1950's (tp 8-8, 9-9, 10-10, 1-1, 1-2, 1-3, 1-4, 2-1, 2-2, 2-3, 2-4, 3-1, 3-2, 3-3, 3-4) and 1970's (tp 11-14, 12-15, 13-16, 1-1, 1-2, 2-3, 2-5, 3-4, 3-6), with decreases generally in both labor and investment. It might also be noted that, with the exception of the more capital-intensive technical packages, the labor force of the 1920's is largely unskilled with skilled men acting in a supervisory capacity, while that of the 1950's and 1970's is fully skilled.

In the above discussion, the piece of excavation equipment has been used as an identifier of the excavation/hauling technical package, and for those packages where the haul equipment is a separate item, it, too,

has changed in much the same way; thus, the hand-powered equipment, 1.5 cubic yard, horse-drawn wagons, 5.0 cubic yard, tractor-drawn wagons, and 3.5 ton trucks of the 1920's are replaced by 8.5 to 15 bank cubic yard, tractor-drawn wagons and 10 to 20 ton trucks in the 1950's and 15 to 27 bank cubic yard wagons and 10 to 35 ton trucks in the 1970's. The impact of the haul vehicle on the performance of the overall package is naturally much greater at the longer haul distances; only in the case of front end loaders, however, does the haul mode seem to have a generally significant effect, in that they perform well doing their own haul for short distances but absolutely require a separate haul vehicle for long distances.

With the exception of the material being used, spreading/compaction and gravel surfacing are very similar stages in that they involve the same basic activities and technical packages, and they can thus be discussed together. The set of technical packages available is not so diversified as is that for excavation/hauling, and the two major activities, spread and compact, are pretty much independent, with the result that the equipment in neither really dominates the performance of the technical packages (as does the excavation equipment in excavation/hauling). As in the case of excavation/hauling, the 1920's technical packages span a broad range of capital/labor ratios, while those of the 1950's and 1970's fall within a very narrow range, the 1970's being noticeably more capital-intensive than the 1950's.

The handtools (spr/comp tp 11, 12; gravel tp 11, 12), horse-drawn blade graders (spr/comp tp 21, 22; gravel tp 21, 22), and tractor-drawn

blade graders (spr/comp tp 32) of the 1920's are replaced by self-powered blade graders (spr/comp tp 31, 32, 33, 34, 41, 42, 43, 44; gravel tp 31, 32, 41, 42), bulldozers (spr/comp tp 11, 12, 13, 14, 21, 22, 23, 24; gravel tp 11, 12, 21, 22), and spreaders (gravel tp 51, 52) in the 1950's and again in the 1970's by somewhat larger and more powerful pieces, each time with some drop in labor but only a small, if any, drop in investment across similar types of spreaders. As for the compacting equipment, heavier versions of existing rollers and new types of rollers are introduced in each period. The 2.5 ton, horse-drawn rollers (spr/comp tp 11, 21; gravel tp 11, 21) and 6 ton, 3 wheel rollers (spr/comp tp 12, 22, 32; gravel tp 12, 22) of the 1920's are replaced by 8 to 12 ton, 3 wheel rollers (spr/comp tp 13, 23, 33, 43; gravel tp 11, 21, 31, 41, 51), tractor-drawn sheepsfoot rollers (spr/comp tp 11, 12, 21, 22, 31, 32, 41, 42), and 10 ton, pneumatic rollers (spr/comp tp 14, 24, 34, 44; gravel tp 12, 22, 32, 42, 52) in the 1950's, while in the 1970's the same or slightly larger 3 wheel (gravel tp 11, 21, 31, 41, 51), sheepsfoot (spr/comp tp 12, 22, 32, 42), and pneumatic rollers (spr/comp tp 13, 23, 33, 43; gravel tp 12, 22, 32, 42, 52) are used, and self-powered sheepsfoot (spr/comp tp 11, 21, 31, 41) and vibratory rollers (spr/comp tp 14, 24, 34, 44; gravel tp 13, 23, 33, 43, 53) are introduced; the effect of these changes on labor is always a decrease across similar rollers, but that on investment varies from some increase to some decrease, depending upon the particular roller being considered, the overall impression being that investment decreases only slightly if at all. As for the labor, the 1920's tends to be mixed although slightly heavier

on the unskilled, while the 1950's and 1970's is skilled except for an occasional unskilled helper. In these two stages, as in the other surfacing stages, the width of the road, as designed in Section 3.2, may be having an effect on the relative performance of technical packages of the 1950's and 1970's which differ only in terms of the size of the spreading equipment; this is not felt to be serious enough, however, to affect the relative performance of various types of spreading and compacting equipment, which is of more interest in any case.

The range of capital/labor ratios for waterbound macadam surfacing is very limited for all three periods. In the 1920's, data for only two technical packages could be found, but these are both considerably more labor-intensive than are those of the 1950's and 1970's; the technical packages for the 1950's fall into two distinct groups depending upon the method of compaction, one being considerably less capital-intensive than the 1970's and the other about the same level of capital intensity. It should be noted that the equipment used in spreading the crushed stone and compacting the surface is the same as that for gravel, except for the 1920's where a heavier roller is used. Waterbound macadam surfacing is that stage of construction which requires a tremendous amount of compaction; it is thus not surprising that the compaction method has a primary influence on the overall behavior of the technical package, resulting in the packages falling into groups around this in the 1950's and around this and the method of spreading screenings in the 1970's. The technical packages of the 1920's involve hand or horse-powered equipment and unskilled men with skilled men as supervisors, with the

exception of the 10 ton, 3 wheel roller. The transition to the 1950's involves, in addition to the equipment noted for gravel surfacing, the introduction of a truck-mounted spreader box (in all technical packages) instead of handtools for distributing screenings and the use of mostly skilled labor with unskilled men as assistants; this occurs with significant decreases in both labor and investment. As for the 1970's, the primary change, in addition to those for gravel surfacing, is the introduction of a gas spreader (tp 111, 112, 113, 211, 212, 213, 311, 312, 313, 411, 412, 413, 511, 512, 513) for distributing screenings; corresponding change in labor and investment varies widely with the particular roller and screenings spreader being considered.

As is the case in waterbound macadam surfacing, the range of capital/labor ratios in the double bituminous surface treatment stage is rather narrow for all three periods, the 1920's being considerably more labor-intensive than the 1950's and 1970's, which exhibit about the same level of capital intensity. Although alternative methods are used for the major activities in each period, the set of technical packages in each period is very close in performance, with the primary influence on their behavior coming from the spreading crushed stone and compacting the surface activities. The transition from the 1920's to the 1950's involves going from handtools to a truck-drawn (tp 1111, 1112, 1121, 1122) or self-powered broom (tp 2111, 2112, 2121, 2122), from a 600 gallon to a 1000 gallon bitumen distributor, from handtools (tp 1111) or a spreader box mounted on a 5 ton truck (tp 1121) to a spreader box mounted on a 10 ton truck (tp 1121, 1122, 2121, 2122) or a gas spreader (tp 1111,

1112, 2111, 2112), and from a 6 ton, 3 wheel roller to a 5-8 ton, tandem roller (tp 1111, 1121, 2111, 2121) or 10 ton, pneumatic roller (tp 1112, 1122, 2112, 2122); as for labor, it is quite mixed in both periods, with the 1920's tending toward more unskilled with a few supervisory types and the 1950's tending toward more skilled with some unskilled assistants. Particularly significant in this transition, however, is the sizeable drop in both labor and investment. As for the 1970's, the equipment is basically the same as or slightly larger and more powerful than that of the 1950's, but there is still a noticeable drop in both labor and investment over this period.

4.11 The Efficient Technical Packages

Given this broad overview of the full set of technical packages, it is now useful to narrow this to those which are efficient, those which produce the most output for the least input, for each stage of construction, for each technology period and over all periods. Two basic approaches to such an efficiency analysis, a graphical and a numerical one, are presented in Section 2.31, and their results are presented as Figure 3.1 and Table 3.4 and Table 3.5, respectively, in Section 3.13. Before discussing these results, it is important to look briefly at these two analytic approaches and consider their limitations and sensitivities in the case at hand.

The graphical approach involves plotting the labor and capital components of the various technical packages for each period which are required to produce a given rate or level of output. The first simplification is the omission of materials, since they are the same across all

technical packages, with the exception of those for site preparation where their share is small enough to warrant their omission as a third dimension in the graphical analysis. The next difficulty is the units of measurement of the resources. Labor can be measured in physical units of unskilled men or unskilled man-hours, where before the skilled is added to the unskilled component, it is weighted by the skilled to unskilled wage ratio at the time of the technical package; the justification for this is the assumption that the wages reflect, in some sense, the relative quality or productive potential of skilled and unskilled laborers, thus necessitating the use of the wage ratio at the time the technical package itself was in use. The 1920's technical packages are the ones potentially most affected by this assumption, in that the 1930 wage ratio is 1.91 compared with 1.34 and 1.25 for 1956 and 1974, respectively. A comparison of the investment plots in Figure 4.1a, where the wage ratio corresponding to the period of the technology is used, and Figure 4.1b, where the 1974 wage ratio is used for both the 1920's and 1970's technical packages, suggests, moreover, that the 1920's technical packages at the 1974 wage ratio have naturally shifted closer to the 1970's technical packages, but their relative positions remain essentially unchanged, and the set of efficient packages is the same. The impact of the wage ratio on the overall results thus seems relatively minor, and that of the period of the technology is used.

Capital's measurement presents even more of a problem because its heterogeneous nature necessitates the use of value measures rather than

Figure 4.1a: Labor, in unskilled men where the skilled are weighted by the wage ratio at the time of the technology, and capital, in investment costs at 1974, required by each technical package for excavation/hauling at 100 meters at the rate of 100 bank cubic meters per hour, for the 1920's and 1970's technologies (source: Table B.6).

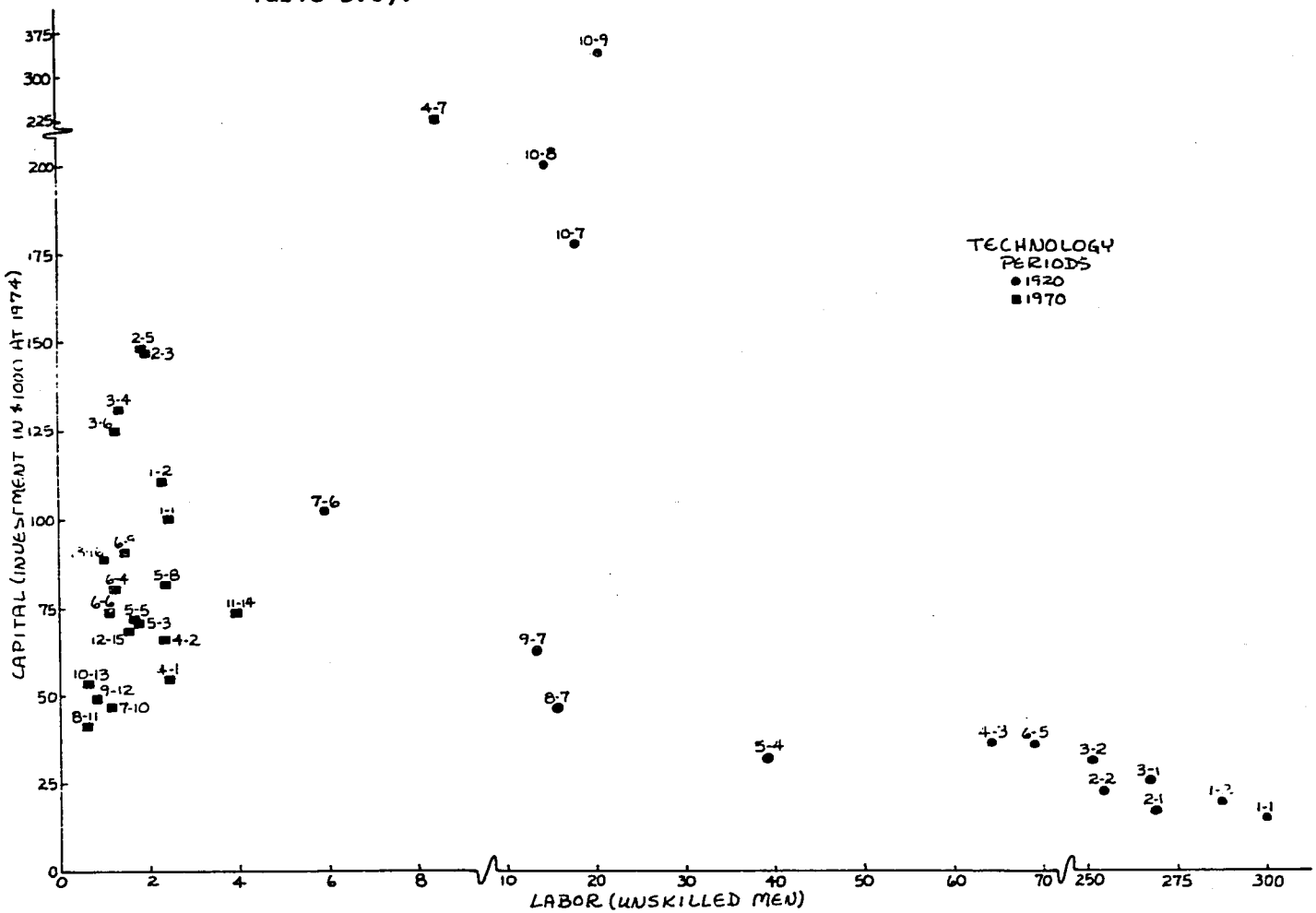


Figure 4.1b: Labor, in unskilled men where the skilled are weighted by the 1974 wage ratio, and capital, in investment costs at 1974, required by each technical package for excavation/hauling at 100 meters at the rate of 100 bank cubic meters per hour, for the 1920's and 1970's technologies (source: Table B.6).

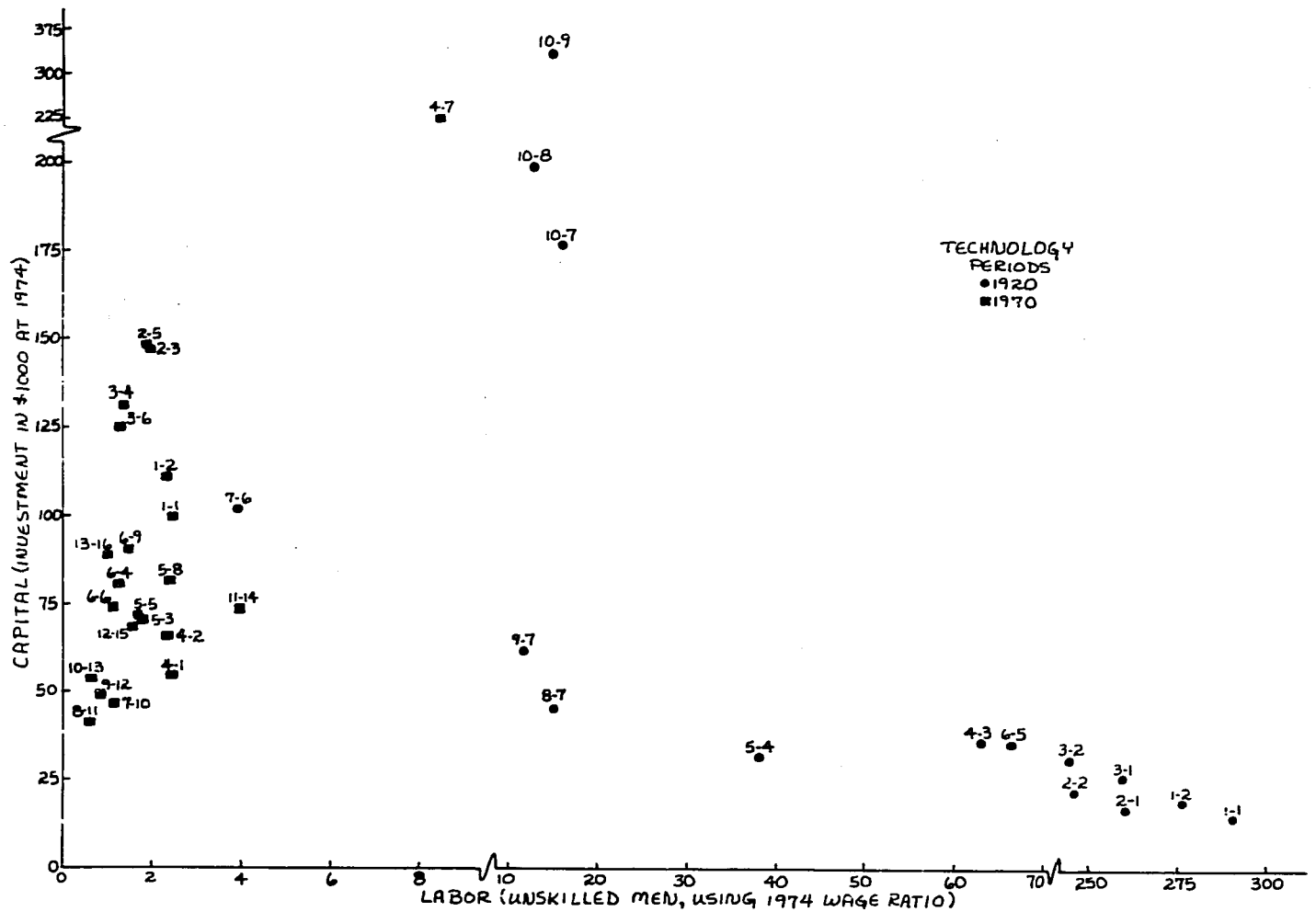


Figure 4.1c: Labor, in unskilled man-hours where the skilled are weighted by the wage ratio at the time of the technology, and capital, in depreciation costs at 1974, required by each technical package for 100 bank cubic meters of excavation/hauling at 100 meters, for the 1920's and 1970's technologies (source: Tables B.6 and B.7).

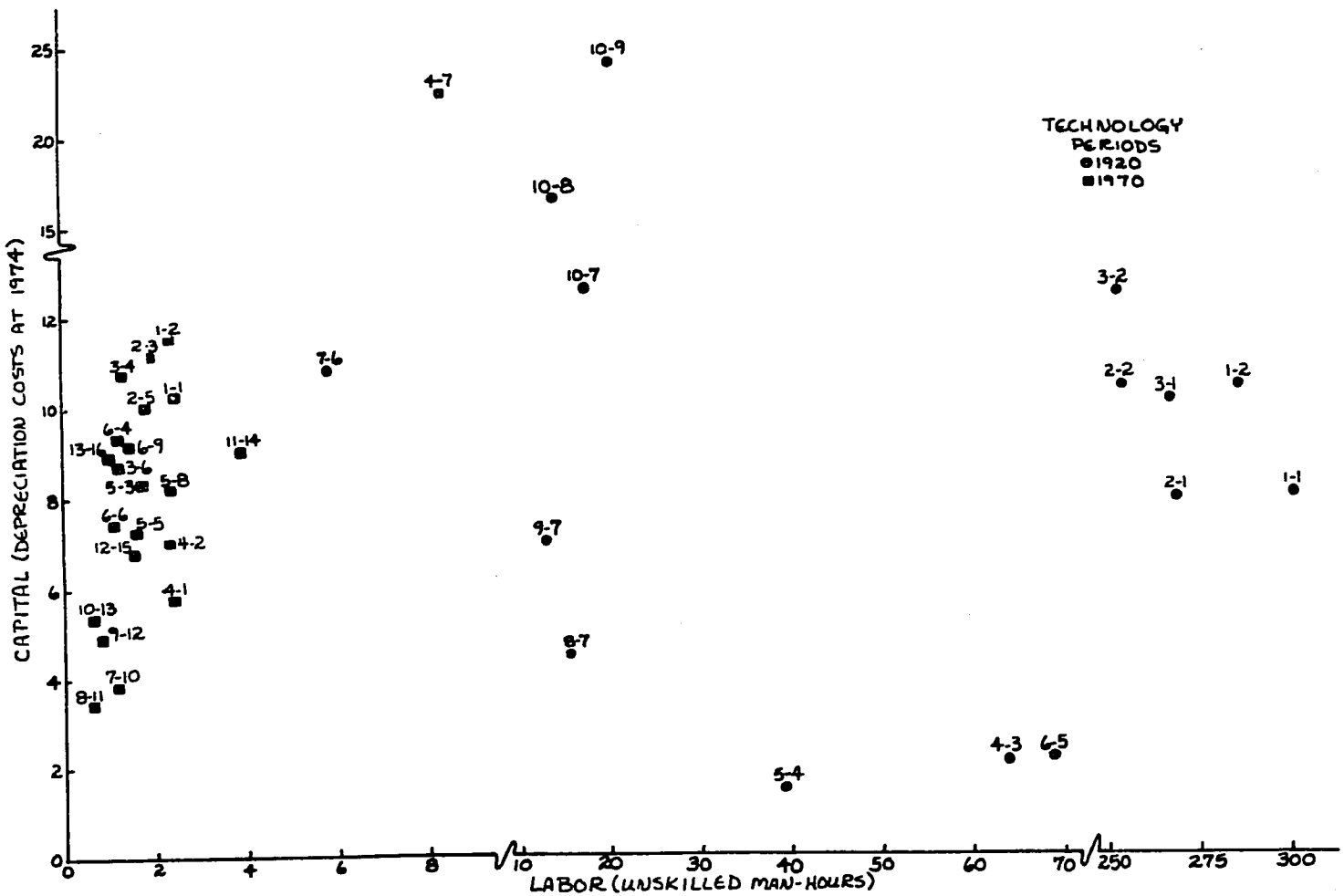


Figure 4.1d: Labor, in unskilled man-hours where the skilled are weighted by the wage ratio at the time of the technology, and capital, in ownership and operating costs at 1974, required by each technical package for 100 bank cubic meters of excavation/hauling at 100 meters, for the 1920's and 1970's technologies (source: Tables B.5 and B.6).

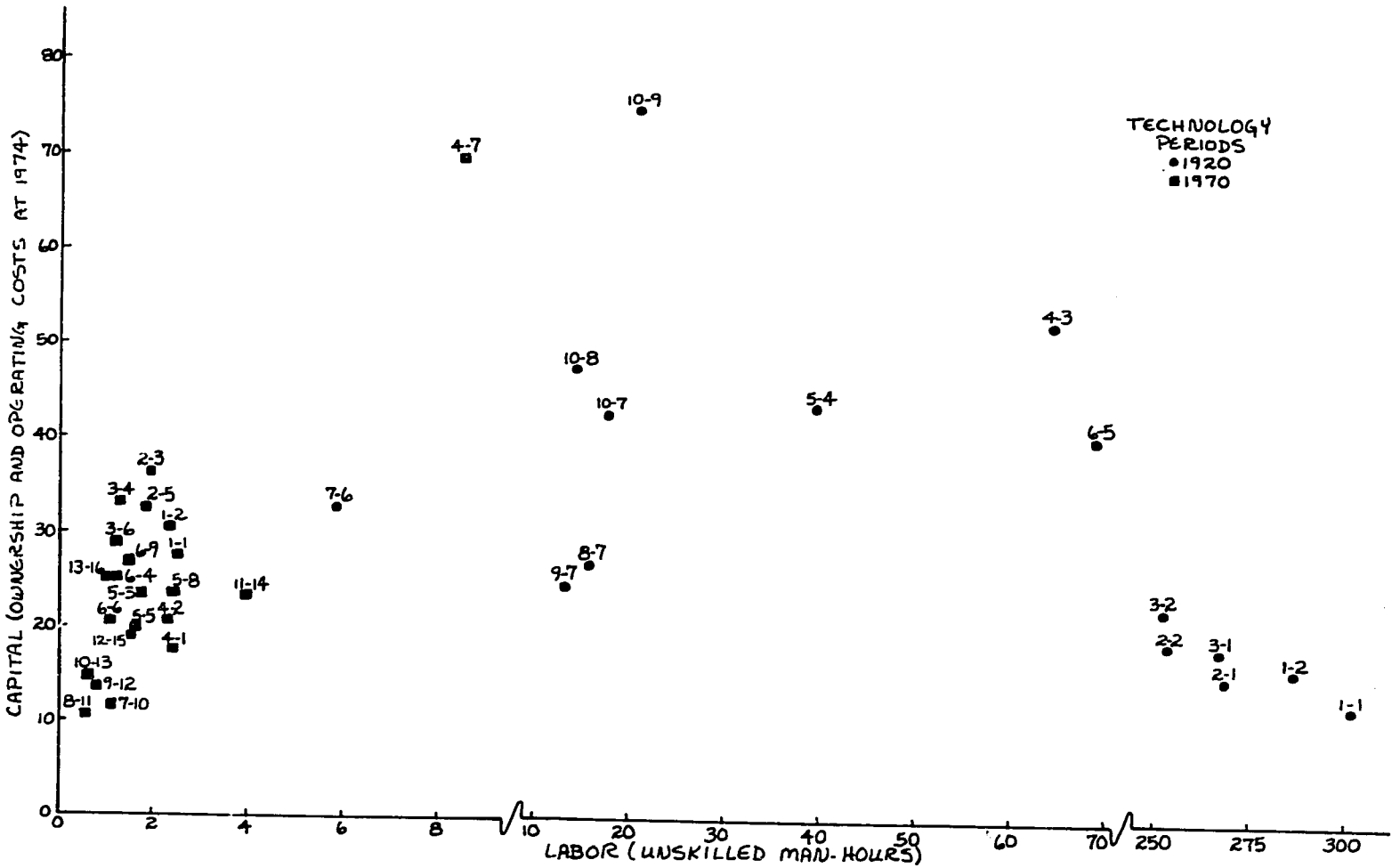


Figure 4.1e: Labor, in unskilled men where the skilled are weighted by the wage ratio at the time of the technology, and capital, in investment costs at 1930, required by each technical package for excavation/hauling at 100 meters at the rate of 100 bank cubic meters per hour, for the 1920's and 1970's technologies (source: Tables B.6 and B.7).

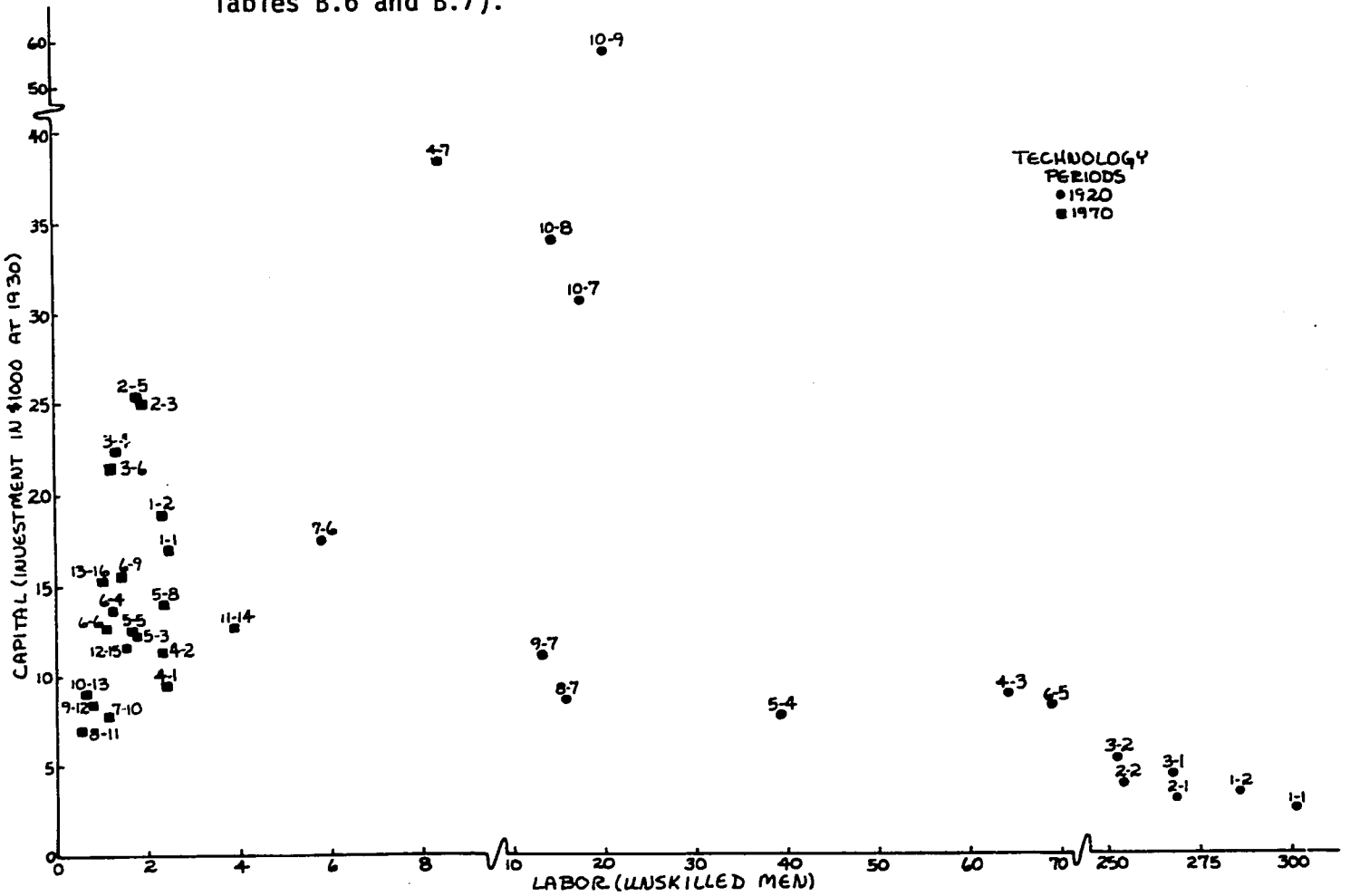
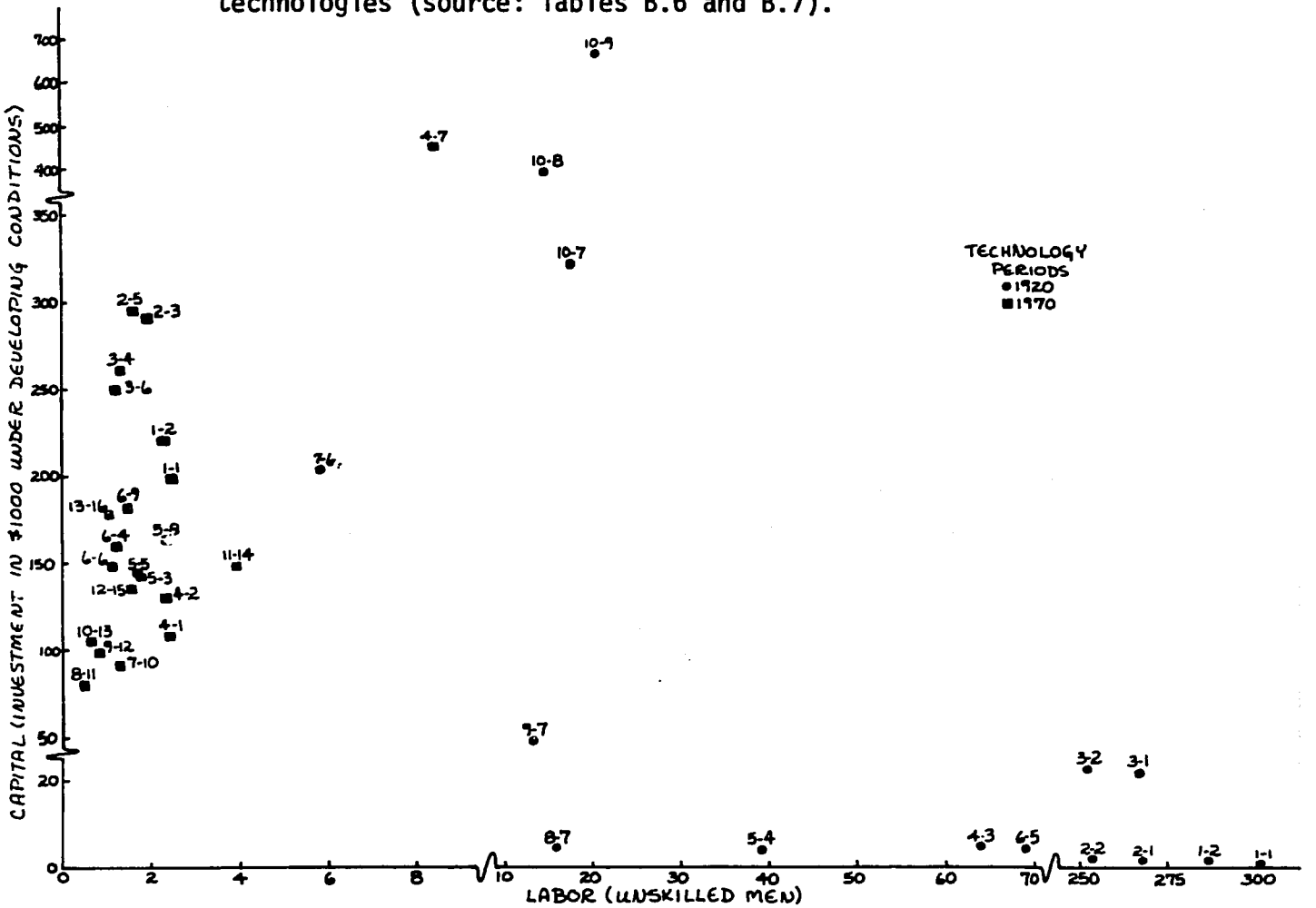


Figure 4.1f: Labor, in unskilled men where the skilled are weighted by the wage ratio at the time of the technology, and capital, in investment costs under developing conditions, required by each technical package for excavation/hauling at 100 meters at the rate of 100 bank cubic meters per hour, for the 1920's and 1970's technologies (source: Tables B.6 and B.7).



physical units. A rather natural measure of capital is its investment cost in that a primary concern in technology change and technology choice is expenditure now, as for capital, versus payments over time, as for labor and materials. This is particularly appropriate in cases where the equipment is quite uniform in terms of lifetime, maintenance as a percentage of investment cost, and fuel consumption, as is somewhat true for the 1950's and 1970's but is decidedly not the case for the 1920's. In order to ascertain the sensitivity of the results to the measurement of capital, a couple of different measures are tried for the 1920's and 1970's technical packages for excavation/hauling at 100 meters. Labor in all cases is measured in units of unskilled men per 100 bank cubic meters per hour or unskilled man-hours per 100 bank cubic meters. Figure 4.1a presents the standard investment plot of investment in 1974 dollars required to produce 100 bank cubic meters per hour; Figure 4.1c introduces the lifetime of the capital resource into its measure by using hourly depreciation costs in 1974 dollars (investment divided by lifetime in hours); finally Figure 4.1d brings in all of the parameters varying with the item of capital by using hourly ownership and operating costs in 1974 dollars.

The only really significant change in the 1920's technology in Figure 4.1c relative to 4.1a is the upward shift in the fully labor-intensive technical packages (tp 1-1, 1-2, 2-1, 2-2, 3-1, 3-2), reflecting the fact that the short lifetime of the handtools involved makes their low investment costs rather expensive in hourly depreciation terms. As for the 1970's some of the packages move slightly relative to one

another, and some of the power shovels (tp 2-3, 2-5, 3-4, 3-6), in particular, shift downward due to their relatively long life, but there is no change in the set of efficient technical packages (tp 8-11), and the overall effect is not too significant. As for hourly ownership and operating costs as a measure, the major change in the 1920's technical packages is the upward shift of the horse-powered technical packages (tp 4-3, 5-4, 6-5, 8-7), suggesting that the upkeep of a horse is expensive although its investment cost is low and lifetime long relative to those of equipment; the handtools (tp 1-1, 1-2, 2-1, 2-2, 3-1, 3-2) have also shifted back to their old position, suggesting that the impact of their relatively short lifetime is neutralized by their relatively low maintenance and operating costs. Changes in the 1970's packages are limited to slight movements of the packages relative to one another, although it should be noted that the 1970's packages are generally lower relative to those of the 1920's, with the 1970 elevating scraper (tp 8-11) being lower in cost than all of the 1920's packages. In summary, it seems that investment is probably the most appropriate measure of capital, at least for a graphical representation, in that it focuses on the issue of present versus future costs and does not seem to somewhat arbitrarily eliminate technical packages from the efficient set, as do the hourly depreciation and ownership and operating cost measures.

Accepting this, the next question is the appropriate base period, the selection of which may also influence the results. Figures 4.1a, 4.1e, and 4.1f respectively present investment plots at the prices of

1974, 1930, and a typical developing country, the latter being included to see what occurs under more extreme conditions than the first two. Equipment investment changes by a factor of 5.86 between 1930 and 1974 while investment in a horse changes by a factor of 3.93; under developing conditions heavy equipment investment goes up by a factor of nearly two relative to 1974, while investment in light equipment and a horse are reduced by nearly a factor of two relative to 1930. The effect is as expected: (1) the 1970's are completely unaffected in terms of their relative positions, since practically all of the capital is heavy equipment; (2) the same is pretty much true for the 1920's packages at 1930 costs; and (3) the 1920's at developing country conditions are significantly affected, in that there is a large space between the largely heavy equipment packages involving the bulldozer (tp 7-6) and power shovel (tp 10-7, 10-8, 10-9) and the remaining largely light equipment packages. The set of efficient packages for each period, however, remains the same with but a few exceptions. The tractor-powered elevating grader (tp 9-7) is added to the 1920's efficient set at developing prices, due to its being partly light equipment; the fresno (1920 tp 5-4) is dropped from the overall efficient set at 1930 prices, due to the smaller change in the cost of the horse relative to that of equipment, while the horse-powered elevating grader (1920 tp 8-7) is added at developing prices, due to its being light equipment. In summary, the base period does not seem to have too significant an impact on the overall results, and 1974 seems as reasonable as any other year for use in pricing the investment plot.

The graphical analysis thus provides one means of identifying the efficient technical packages, but because of the measurement difficulties discussed above, particularly the sensitivity of the results to the method of measuring capital, a second means is seen as necessary, this being the numerical analysis. Holding the engineering variables (i.e., resource productivities and basic equipment characteristics) constant while varying the economic variables (see Table 3.3) over a wide range, the efficient technical packages are those which appear as least cost under at least one reasonable set of economic conditions. The first problem, of course, is developing a comprehensive set of economic conditions, such that the various combinations which can arise represent the majority of possible real world situations. Recognizing the difficulty of doing this with a reasonably sized set of conditions, it must be realized that the set of efficient technical packages is thus restricted by the particular conditions used in the numerical analysis; other packages might enter the efficient set if additional economic conditions were included or some enter and some leave the efficient set if the conditions were modified somewhat. This latter situation is particularly likely among those technical packages which are relatively close in cost, such as the handtools (tp 1-1, 1-2, 2-1, 2-2, 3-1, 3-2) in the 1920's and certain of the waterbound macadam surfacing and double bituminous surface treatment packages in the 1950's (wbm tp 112, 212, 312, 412, 512; most dbst tp's) and 1970's (wbm tp 111, 211, 311, 411; most dbst tp's). This brings up another difficulty with the numerical analysis. It is set up so as to identify only one

technical package for each combination of economic conditions, even if the costs of others are in very close proximity; modification of this to include all packages within 10 percent, for example, might help alleviate some of the potential sensitivities of the results.

Between the graphical and numerical analyses, nevertheless, it seems quite possible to develop a reasonably reliable picture of the set of efficient technical packages for each stage of construction, for each period and over all periods. Most of the differences in the results of these two analyses, as given in Tables 3.4 and 3.5, arise as a result of the measure of capital selected in the graphical analysis. Several of the 1920's packages which arise only in the numerical analysis would arise in the graphical if it were done at developing rather than 1974 conditions; the remainder arise under economic conditions which depict reasonable scenarios, such as a typical developing country except for expensive light as well as heavy equipment and/or expensive beasts of burden, among others, as discussed in Section 3.13, but which are not represented by any of the capital measures considered above. The differences in the results of the 1950's and 1970's stem largely from the use of investment rather than hourly depreciation or ownership and operating cost as the measure of capital. For example, the investment required for a particular technical package may be relatively low, but its lifetime may also be relatively low and/or its fuel consumption high, resulting in high hourly costs; the outcome is that it looks efficient in the graphical analysis but does not appear as least cost in the numerical analysis. Another situation which occurs just a couple of

times in the 1970's (exc/haul tp 4-1; spr/comp tp 31) is that a technical package shows up as efficient in the graphical analysis when, in fact, it is barely efficient, since its investment is essentially the same as that of another package which has significantly less labor; finally, the two extra site preparation packages for the 1950's and 1970's arise in the graphical but not in the numerical analysis because investment for the two packages is less than for package 31 each year, but labor is significantly more, and the economic conditions in the numerical analysis are never apparently such as to override the low productivity of the package relative to that of 31. As for the results of the analyses over all periods, the packages which appear naturally follow directly from those which appear in the individual periods, and similarly, the same basic explanations account for any differences in the results of the two analyses.

The set of efficient technical packages in the 1920's, then, is observed to span a broad range of capital/labor ratios and unit costs. The efficient sets in the 1950's and 1970's, on the other hand, are represented by only a few packages generally, with capital/labor ratios and/or unit costs in close proximity, sometimes so close that the packages are essentially indistinguishable; this closeness comes to a peak with the waterbound macadam surfacing and double bituminous surface treatment stages, where several technical packages (1950 wbm tp 112, 212, 312, 412, 512; 1970 wbm tp 111, 211, 311, 411; most 1950 dbst tp's; most 1970 dbst tp's) are within 10 percent in unit cost, making the efficiency analysis rather meaningless as the entire least-cost set is really efficient.

The efficient set for each stage of construction in the 1920's technology includes the full production set except for the excavation/hauling stage where certain representative technical packages are included; at 6 meters, handtools (tp 1-1), scrapers (tp 4-3, 5-4), and bulldozers (tp 7-6) are represented, at 100 meters, handtools (tp 1-1, 1-2), scrapers (tp 5-4), elevating graders (tp 8-7, 9-7), and bulldozers (tp 7-6), and at 800 meters, handtools (tp 1-1, 1-2, 2-1, 2-2), scrapers (tp 6-5), elevating graders (tp 8-7, 9-7), and power shovels (tp 10-8). This is not the case for the 1950's and 1970's where the efficient set consists of only a couple of technical packages and thus a couple of types or sizes of equipment, except for the double bituminous surface treatment stage where all packages are essentially included. Site preparation thus goes from handtools (tp 11) or a bulldozer (tp 21) in the 1920's to larger bulldozers in the 1950's (tp 31) and 1970's (tp 21, 31), although a handtools package (tp 11) also appears as graphically efficient in the 1950's. In excavation/hauling at 6 meters, successively larger bulldozers are used in the 1950's and 1970's, while at 100 meters scrapers take over, and at 800 meters an elevating grader takes over in the 1950's while the larger scrapers stay on in the 1970's. Finally in the spreading/compaction, gravel surfacing, and waterbound macadam surfacing stages, the handtools and early blade graders of the 1920's are replaced by larger, self-powered blade graders for spreading soil and aggregate (although, as noted above, any spreading tool can be used in waterbound macadam) and spreader boxes or gas spreaders for spreading screenings in the 1950's and 1970's; the

horse-drawn and small, 3-wheel rollers of the 1920's, in turn, are replaced by larger, 3-wheel and pneumatic rollers in the 1950's and self-powered, sheepsfoot rollers in the 1970's for compacting soil and pneumatic rollers in the 1950's and larger, 3-wheel and pneumatic rollers in the 1970's for compacting aggregate.

More interesting, perhaps, than looking at the transition over time in the efficient sets of technical packages for each stage of construction is looking at the efficient set which arises when the technical packages of all periods are considered at once. The full set of efficient, 1970's technical packages are, not surprisingly, included in this set, but also included are certain of the more labor-intensive and animal-powered packages of the 1920's (at least through gravel surfacing), while only a couple of the 1950's packages are included. A reasonable explanation for the exclusion of the 1950's technical packages is that they are, by and large, very similar to those of the 1970's; their capital/labor ratios are about the same or only slightly less than those of the 1970's, especially compared with the 1920's-1970's gap, and the equipment involved is often just a little smaller or a slightly different type and somewhat less productive but still powered and requiring skilled labor. The technical packages of the 1920's which show up, on the other hand, are very different from those of the 1970's, being fully labor-intensive or at most labor assisted by horse-powered equipment. It is under developing conditions, then, that the 1920's packages arise as least cost. It might be noted, however, that (1) some of the most labor-intensive packages (exc/haul 6M tp 1-1;

spr/comp tp 11; gravel tp 11) which in the 1920's set arise under developing conditions with an expensive horse, (2) two of the horse-powered technical packages (exc/haul 6M tp 4-3; 800M tp 6-5) which in the 1920's set arise under developing conditions where light and heavy equipment are equally costly, and (3) all packages which involve any powered equipment (all remaining excluded technical packages) still cannot compete because of their very low productivity relative to that of the 1950's and 1970's packages. Although the 1920's technical packages for waterbound macadam surfacing and double bituminous surface treatment are labor-intensive relative to those of the 1970's, the gap is not so large as in the other stages and powered equipment is involved in all cases, resulting in their exclusion from the overall efficient set.

In summary, the results of the efficiency analysis demonstrate the existence of a production set that can be described as a production function for most stages of highway construction in the 1920's, the exceptions being site preparation, waterbound macadam surfacing, and double bituminous surface treatment. Only two packages are identified for each of these latter stages, as that was the limit of the available data, although it seems likely that other packages may have been in use. It might be noted at this point that much of the technology of surfacing is in the material being used, and that there is often not the variety of ways to produce a particular surface, especially the higher standard surfaces, as there is to do earthworks, for example. For the 1950's and 1970's, on the otherhand, there really are no production

functions except maybe for site preparation, where three packages are identified, with two being efficient according to the graphical analysis. It is felt that this lack of production functions, however, does not stem from a lack of data, in that a reasonably large number of technical packages are identified for each stage, with a couple of different types as well as sizes of equipment, with the possible exception of double bituminous surface treatment for which at most two items of equipment are identified for each major activity. The implication, then, is that this lack depicts a real shortage of efficient alternatives and the focusing of the development of new technical packages on a particular capital/labor ratio.

As for the overall analysis, if one accepts the results of the numerical analysis or a combination of the two, then, once again production functions exist, with the exception of double bituminous surface treatment, but these are production functions with a large gap in the middle, going from the fully labor-intensive and animal-powered technical packages of the 1920's to the fully capital-intensive packages of the 1970's, with a couple having a 1950's package, much closer to the 1970's, in between. It is also expected that these 1920's packages will arise as least cost only under the rather extreme types of developing conditions outlined in this research. Nevertheless, there does at least seem to be some possibility of a few rather labor-intensive packages being efficient relative to today's technology.

4.12 The Best-Practice Technical Packages

In order to more directly investigate the issue of efficiency and

substitution and their role in technology change, it is necessary to narrow the set of efficient technical packages in the 1920's, 1950's, and 1970's to the set of best-practice packages for each stage of construction at the prices of 1930, 1956, and 1974 as given in Table 3.6. This is done by applying the factor prices of each of these periods to the resource requirements of each technical package, the best-practice packages being those which are minimum cost, or at least within 10 percent of it, in terms of the production function and the relative factor prices. Movements over time of the best-practice package for a particular stage of construction, then, represent technology change.

Before proceeding to investigate technology change in some detail, it is useful to consider the magnitude of the change that has occurred over the years in terms of overall costs and factor inputs, the results being presented in Figures 3.2 and 3.3. Figure 3.2a shows the progression of the unit costs of each stage of construction over time, both as it actually occurred and as it would have occurred had technology not changed as it did. From the 1920's best-practice packages at 1930 prices to the 1950's packages at 1956 prices, the general trend in unit costs is steady to some decline, suggesting that the some four-fold increase in labor, nearly three-fold increase in equipment investment, and practically no to a two-fold increase in other items (e.g., fuel and interest) costs have been fully, or even more than fully, offset by the change in technology. Between the 1950's and 1970's, on the other hand, unit costs have roughly doubled, indicating that technology change has succeeded only in part in offsetting the better than

three-fold increase in labor, two-fold increase in equipment investment, and two to three-fold increase in other items costs. In line with this is the broad divergence in unit costs of the 1920's and 1950's best-practice packages at the three price periods and the nuch narrower difference in those of the 1950's and 1970's packages. At the same time, it should be noted that the best-practice packages in the 1920's are the most capital-intensive ones of the efficient set.

The impact of technology change seems to be somewhat less in the cases of site preparation and excavation/hauling at 6 meters, as is further indicated by the somewhat narrower span in unit costs between the 1930's technology at the prices of 1956 and 1974 and the technologies which were actually used in those periods, than is the case for the other stages (see Figure 3.2a). This is not too surprising in that the technical packages for both of these stages are quite similar over all three periods, differing not in the type of equipment (largely bulldozers), but only in its size and productivity.

The excavation/hauling at 800 meters, gravel surfacing, and double bituminous surface treatment stages, on the other hand, exhibit a strong influence on the part of technology change between the 1920's and later period technologies, as is evident from Figure 3.2a. In the case of excavation/hauling, this is not surprising as both the excavation (power shovel versus elevating grader versus elevating scraper) and transport (5 cubic yard wagon towed by 20 horsepower tractor versus 15 cubic yard wagon towed by 185 horsepower tractor versus 21.5 cubic yard elevating scraper) equipment are vastly different in type, capacity,

and speed over the three periods. This is a stage of highway construction in which truly significant advances have been made in technology.

As for gravel surfacing, the difference lies primarily in the spreading equipment, going from a 5 foot, horsedrawn blade grader and handtools in the 1920's to 10 to 14 foot, self-powered blade graders in the 1950's and 1970's. Similar behavior might be expected in water-bound macadam surfacing, where the spreading equipment varies over a wide range (from 5 foot, horse-drawn blade graders in the 1920's to 10 to 14 foot, self-powered blade graders, 8 to 14 foot bulldozers, or gas spreaders in the 1950's and 1970's for the crushed stone; from handtools in the 1920's to spreader boxes in the 1950's to gas spreaders in the 1970's for screenings), but the domination of the compaction activity, where the equipment is more similar (10 ton, 3 wheel versus 10 ton, pneumatic versus 12 ton, 3 wheel rollers), overshadows this difference somewhat. As noted earlier, data on surfacing in the 1920's is somewhat sparse, and it is suspected that somewhat more advanced equipment may have existed for spreading aggregate as it did for spreading soil (e.g., the 12 foot blade grader towed by a 76 horsepower tractor-tp 32). In the case of double bituminous surface treatment, the technical packages over the three periods do not seem so far apart, going from hand to power-operated brooms, from 600 to 1000 or 1500 gallon bitumen distributors, from spreader boxes with 5 ton trucks to gas spreaders with 20 ton trucks or spreader boxes with 10 ton trucks, and from 3 wheel to pneumatic or tandem rollers; the effect of technology change, nevertheless, seems to be cumulative, although it should

be noted that the really major differences in productivity are again in the spreading aggregate activity, where it is suspected that the productivity may be somewhat low for the 1920's due to a paucity of reliable data.

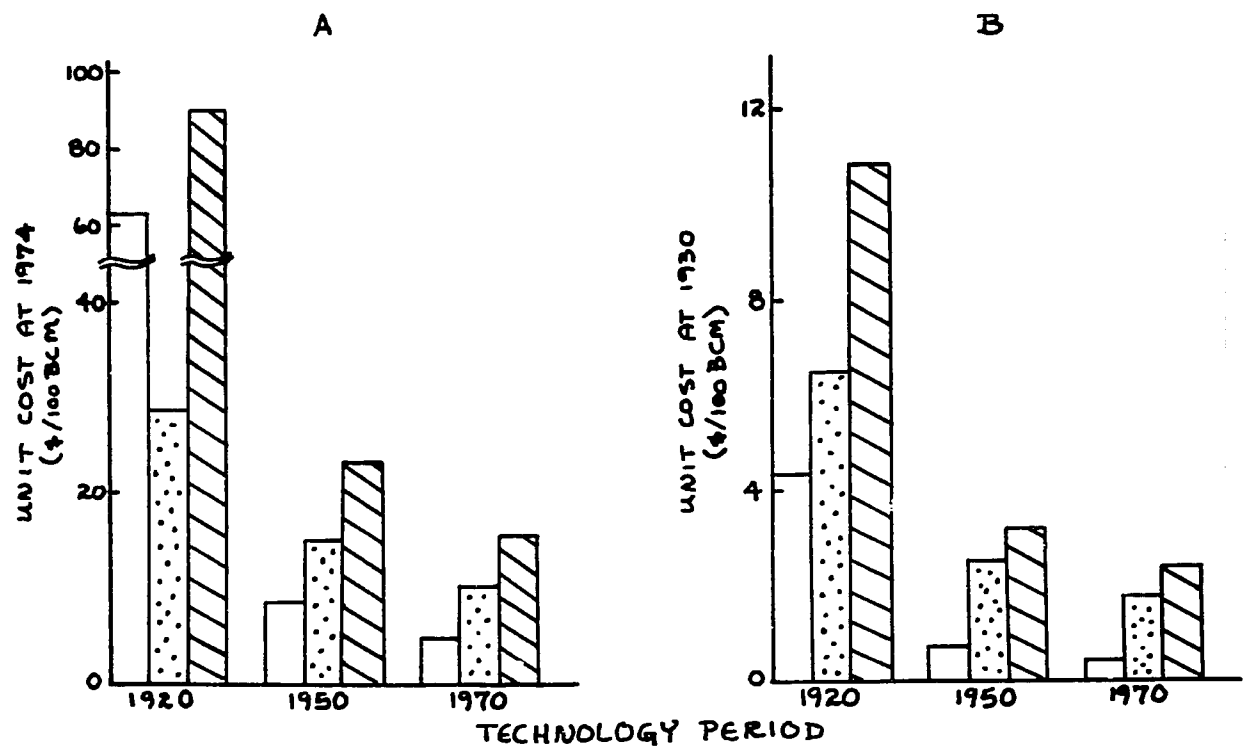
It is important to note, at this point, that much of the analysis of technology change in this section is done using the set of best-practice technical packages for each technology period. Quite justifiably, there is some concern that the magnitude of technology change and its effects might be somewhat overstated, in part because the best-practice rather than average-practice packages are being used, and also because one can feel somewhat more confident that the best-practice packages have truly been identified for the 1950's and 1970's than that the same has been done for the 1920's. At the same time, it should be noted, by looking at Figure 3.2a, that reasonably significant advances in technology are still evident in the pattern of unit costs over time for most stages of construction, even under the assumption that the productivity data for the 1920's are unfairly low relative to those of the 1950's and 1970's, and that they should thus be doubled, halving the unit costs of the 1920's best-practice packages. Site preparation and excavation/hauling at 6 meters are, to some extent, exceptions, but then doubling their 1920's productivities is also less justified, in that the packages of the 1920's in these two stages are so similar to those of the 1950's and 1970's that they are quite likely the truly best-practice ones.

In looking at what lies behind the trends in unit costs observed

in Figure 3.2a, it is useful to look at the labor and capital shares of production. Figure 3.2b does this directly by presenting graphs of labor and capital shares of unit costs in 1974 dollars for the best-practice packages in each technology period. The use of a particular price period with all three technologies has certain difficulties, however, as demonstrated by Figure 4.2, part A, where 1974 unit costs are used, and part B, where 1930 prices are applied; a comparison of these two figures suggests that 1974 prices tend to overstate labor's share relative to that of capital while 1930 prices tend to understate it.

Figure 3.3 presents an alternative approach to looking at labor and capital shares in terms of the relative quantities of these resources required over time. Figure 3.3a, thus, presents the labor measured in unskilled men and capital measured in 1974 investment dollars required by the best-practice packages of each technology period as a percentage of those of the 1920's; Figure 3.3b does the same, using the 1950's as the base. Before deciding upon men and investment as the labor and capital measures, a wide variety of such measures were tried, as demonstrated in Figure 4.3. Comparison of the results produced by the various measures suggests that men and investment are the most reasonable pair to use, as they tend to understate the changes in capital, although at the same time, they slightly overstate the changes in labor. The only other measures of labor are 1930 and 1974 unit costs, and while one of these might be better in terms of changes in labor, they both seem to rather seriously overstate the changes in capital. Moreover, men and investment are the

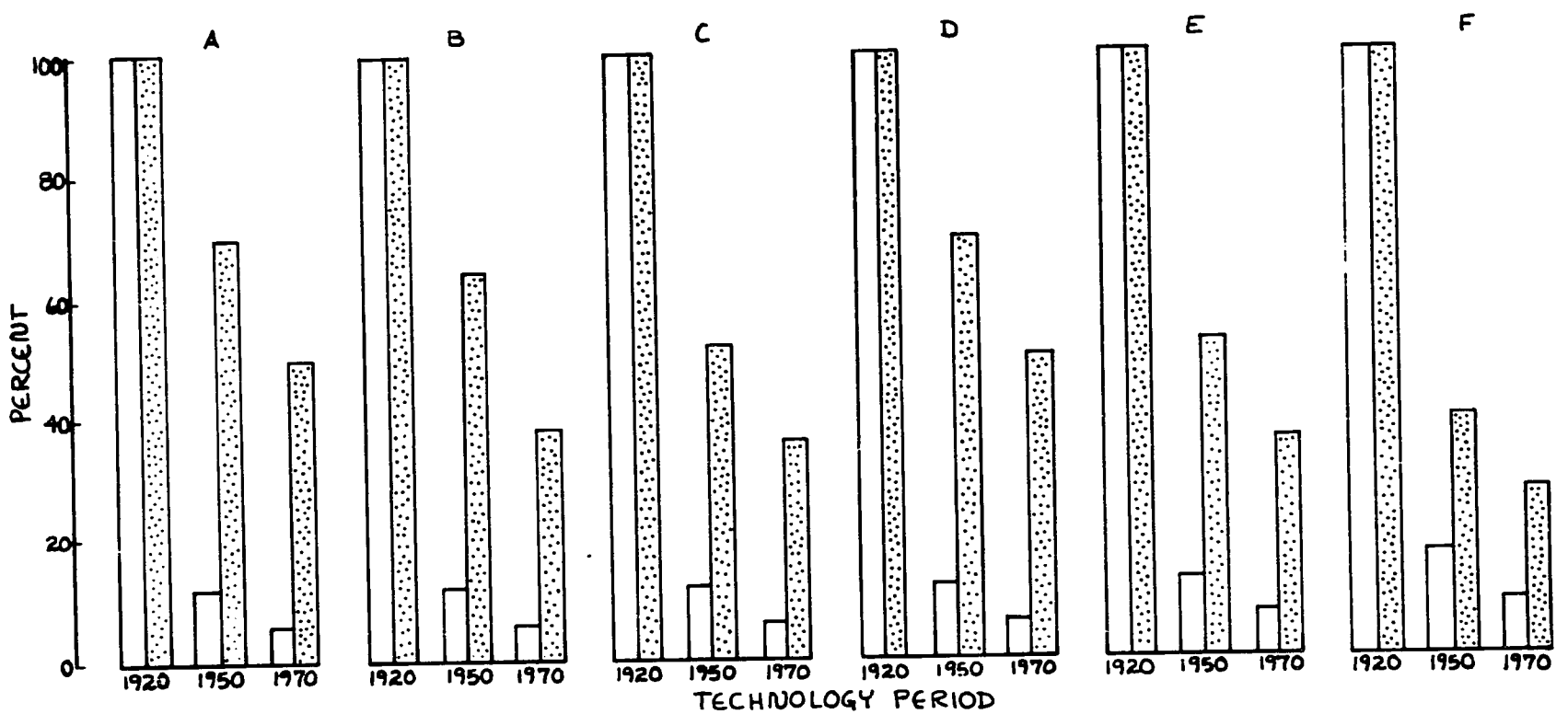
Figure 4.2: Labor and capital components of the unit costs of the best-practice technical packages of each technology period for excavation/hauling at 100 meters, at the prices of 1974 and 1930 (source: Table B.5).



Note: Unit costs: ☐ labor, ⊡ capital, ▧ total.

Best-practice packages are those which appear as least-cost, or within 10 percent of it, at the prices of the period coincident with that of the technology; where more than one package is involved, the data for the various packages is averaged.

Figure 4.3: Labor and capital requirements of the best-practice technical packages of each technology period as a percentage of those of the 1920's, for excavation/hauling at 100 meters, using various measures of labor and capital (source: Tables B.5, B.6, and B.7).



(Figure 4.3 continued)

Note: ☐ percent of 1920's labor; ▩ percent of 1920's capital.

Units of measure:

Part	Labor Input	Capital Input	Product Output
A	unskilled men	investment costs at 1974	100 BCM/hr
B	unskilled man-hours	depreciation costs at 1974	100 BCM
C	unskilled man-hours	ownership and operating costs at 1974	100 BCM
D	unskilled men	investment costs at 1930	100 BCM/hr
E	labor costs at 1974	ownership and operating costs at 1974	100 BCM
F	labor cost at 1930	ownership and operating costs at 1930	100 BCM

Best-practice packages are those which appear as least-cost, or within 10 percent of it, at the prices of the period coincident with that of the technology; where more than one package is involved, the data for the various packages is averaged.

standardly accepted measures in the economic literature, and in the case of the best-practice technical packages, the use of investment as a capital measure is less serious, in that the equipment in the 1920's packages falls somewhat more in line with that ofthe 1950's and 1970's in terms of lifetime, maintenance as a percentage of investment, and fuel consumption.

In the overview of the production sets of the 1920's, 1950's, and 1970's at the beginning of Section 4.1, a general trend was observed of labor decreasing significantly in the transition among technologies, especially between the 1920's and 1950's, while investment behaved in a more varied manner, ranging from some increase to no change to some decrease, for the various stages of construction, with the exception of site preparation where capital and labor switched roles. In the case of the best-practice packages, as given in Figures 3.2b and 3.3, the general trend observed is one of both labor and capital decreasing with changing technology, although a few exceptions in the case of capital show up between the 1950's and 1970's in Figure 3.3. It is also observed that the decrease between the 1920's and 1950's is generally more than that between the 1950's and 1970's, and that the decrease in labor is generally greater than that in capital.

In investigating the capital intensity of various stages of construction and its change over time, one comes to the same basic conclusions whether one looks at the share of unit costs attributed to capital and to labor in Figure 3.2b or one looks at the capital/labor ratios in Figure 3.3. The trend in capital/labor ratios is a steady

increase with changing technology, the most marked increases generally occurring between the 1920's and 1950's; site preparation is an exception in that the ratios fall over time. The distinct differences between the stages show up in the magnitude of the ratio; for excavation/hauling it is some 70,000 to 90,000 investment dollars per man in the 1970's, while for surfacing it is only 14,000 to 16,000 dollars per man, with spreading/compaction falling in between at 24,000 and site preparation on the bottom at 5,500. The implications of this are that the earthworks activities, particularly excavation/hauling, have a strong tendency toward capital intensity, to the point of practically totally replacing labor with capital, while the surfacing activities, at least under current conditions, simply cannot be executed with such a high level of capital intensity, although what is used in the 1970's is certainly much greater than that in the 1920's. As for site preparation, it has a strong tendency toward capital intensity in the brush and tree removal activity, but the burning of the debris activity has remained a highly labor-intensive operation, requiring 30.0 out of the 34.3 unskilled men required to clear 1 hectare per hour in the 1970's. It might also be noted at this point that the technology change which has occurred in highway construction between the 1920's and 1970's obviously has components of both neutral and non-neutral change.

Returning to the list of best-practice packages presented in Table 3.6, it is observed that, with but a few minor exceptions, the best-practice package(s) for each stage of construction in each technology period is (are) the same for all three price periods. The

exceptions consist of the deletion or addition of a technical package and/or modification of the order of the packages in the best-practice set. It is noteworthy that the few changes with price that do occur generally do so in the direction of increasing capital intensity over time; among the double bituminous surface treatment packages, for example, there is some tendency for those with higher capital/labor ratios to start at the end of the list, or not even on it, at 1930 prices and to move up, such that at 1974 prices they are at the top of the list. This meager suggestion of substitution of capital for labor over time is the only introduction of any substitution among alternative packages in each technology period for this price range.

This is not surprising for the 1950's and 1970's, as it was already observed in Section 4.11 that production functions do not really exist for these technology periods, or, in other words, that they have an elasticity of substitution of zero. As for the 1920's, where the technical packages form production functions for most of the stages of construction, these, too, are effectively right-angle production functions with zero elasticity of substitution over this price range. Finally, the 1970's best-practice packages are also the overall least-cost packages for all three price periods, yielding another effectively right-angle production function. It appears that substitution, brought about by changes in factor prices between 1930 and 1974, has not played a significant role in the technology change that is observed over that period.

Efficiency is the next aspect of technology change that is of

interest, ignoring for the moment any potential economies of scale. It must be noted, however, that efficiency cannot be the whole story since, as observed above in conjunction with Figures 3.2b and 3.3, non-neutral as well as neutral technology change has occurred; with the possibility of substitution brought about by factor price changes eliminated, factor bias is left. A method, based on that of Salter (73) of separating the impact of efficiency and bias on proportionate changes in factor inputs is presented in Section 2.31, and the results of this analysis are given in Table 3.7. A few observations about the analysis need to be made before discussing the results.

In line with Salter's approach and Figure 3.3, the quantity of labor is measured in unskilled men and that of capital in 1974 investment dollars; the figures in the table thus represent the change (decrease [-] or increase [+]) in the number of men or amount of investment required by the best-practice packages from one technology period to the next as a percentage of the quantity required in the earlier period, and the distribution of this percentage change between efficiency and bias. Two measures of bias appear in the table, one derived using Salter's approach, and the other derived as the difference between the total percentage change in resource quantities that is actually observed between the 1920's and 1950's and the 1950's and 1970's as given in Figure 3.3 and the percentage change attributable to efficiency as given in Table 3.7. Salter's measure is but an indication of the direction and potential magnitude of bias' influence on the resource quantities, and is generally larger than that actually observed, particularly in the 1920's to 1950's transition where capital/labor

ratios are widely different.

Since Salter's measure of bias serves only as an indicator, the slight variations that might arise, from the use of quantity measures other than unskilled men and 1974 investment dollars, price periods other than that of the earlier of the two technology periods being considered, and so forth, are of relatively little concern. As for the measures of bias derived from Figure 3.3, the use of men and investment as labor and capital measures is discussed above in conjunction with the figure. The measure of efficiency involves a comparison of the costs of using the best-practice packages of the two technology periods being considered, and thus the pricing of the inputs. Table 4.1 gives the results of various pricing methods; no real trend in terms of the pricing method used appears in the results, which are reasonably close together (with the exception of the 1950's to 1970's case of pricing skilled and unskilled labor hours separately and capital hours with hourly ownership and operating costs). For a variety of reasons, the first pricing alternative is used in the analysis. It is Salter's recommendation, as in much of the economic literature, that labor be priced with wages and capital with the capital recovery factor at the prices of one of the two technology periods. This brings out the fixed costs of capital, those costs which are incurred whether or not the equipment is in use. Moreover, since capital recovery factors specific to each particular item of capital are used in this study, the lifetime of the equipment is thus included, and as noted in conjunction with Figure 3.3, the equipment in the best-practice packages of the

Table 4.1: Testing the sensitivity of the percentage change due to efficiency to various means of pricing the labor and capital inputs in the case of excavation/hauling at 100 meters (source: Tables B.5 and B.6).

Pricing Alternative	Percentage Change Due to Efficiency	
	$100 \cdot \frac{Resource_{50} - Resource_{20}}{Resource_{20}}$	$100 \cdot \frac{Resource_{70} - Resource_{50}}{Resource_{50}}$
Labor: priced by skilled and unskilled wages at 1930 or 1956 Capital: priced by capital recovery factor at 1930 or 1956	-69.9	-41.8
Labor: priced by skilled and unskilled wages at 1930 or 1956 Capital: priced by ownership and operating costs at 1930 or 1956	-70.0	-34.6
Labor: measured in unskilled men, priced by unskilled wages at 1930 or 1956 Capital: priced by capital recovery factor at 1930 or 1956	-73.3	-43.4
Labor: priced by skilled and unskilled wages at 1956 or 1974 Capital: priced by capital recovery factor at 1956 or 1974	-75.4	-41.3

Note: Equations for calculating these values are given and discussed in Section 2.31.

1920's is somewhat more in line with that of the 1950's and 1970's than is the full set of 1920's equipment. As for the pricing period, that of the earlier technology in the pair is used, as this is more compatible with the next step of determining the percentage change in resource quantities attributable to substitution brought about by factor price changes (if there were any to observe). Finally, the results obtained with this pricing alternative tend toward under rather than overstating the percentage change attributable to efficiency.

In order to begin to look at the relative roles of efficiency and bias in changing resource requirements over time, it is helpful to see it graphically as well as numerically. In Figure 3.3, using the results from Table 3.7, a dashed line is drawn indicating the level to which the quantities of labor and capital, of the 1950's and 1970's relative to those of the 1920's and 1950's, respectively, fell due to efficiency; the further drop, generally of labor, below this line and rise, generally of capital, above it represent the changes due to bias. It is evident from Figure 3.3 and Table 3.7 that twice in the 1920's to 1950's transition the measure of efficiency appears to be too small, and once in the 1950's to 1970's it appears to be too large. As indicated by the above discussion pertaining to alternative labor and capital measures and prices, this is undoubtedly a function of the particular measures and prices used; moreover, averaging over the best-practice technical packages, when there is more than one in a technology period, probably does not help the coordination of the various measures of change in Table 3.7 and Figure 3.3. The implication of this

is simply that these measures of efficiency and bias should not be interpreted as absolute values, but rather as "ballpark" figures serving as a reliable indication of the relative roles of efficiency and bias in technology change.

The percentage decrease in resources required which is attributed to efficiency ranges from 36 percent for site preparation to 54 to 85 percent for earthworks to a peak of 79 to 90 percent for surfacing in the 1920's to 1950's transition (see Table 3.7 and Figure 3.3). These same figures for the 1950's to 1970's are significantly less, ranging from only 15 to 55 percent, and the positions of earthworks and surfacing are switched. Looking at the figures for total percentage change in resource quantities, as taken directly from Figure 3.3, the same basic trends are observed and were noted above in the discussion of Figure 3.3. Combining these two sets of data for labor (capital in the case of site preparation) yields the change in the quantity of labor (capital) attributed to efficiency as a share of the total change. In the 1920's to 1950's transition, this is some 66 percent for site preparation, 79 to 91 percent for earthworks, and 89 to 96 percent for surfacing; site preparation and excavation/hauling at 6 meters are notably less, being 46 to 54 percent, respectively, for the 1950's to 1970's transition, but the other stages exhibit about the same, or only a slightly smaller, percentage of total change in labor attributed to efficiency over this period. The role of bias toward labor-saving in the change in the quantity of labor required over the transition periods is thus relatively small, representing only 4 to 21 percent of the

change and being about the same or slightly more in the 1950's to 1970's than in the 1920's to 1950's. As for site preparation, the technologically constant burning activity creates an appearance of bias toward capital-saving or labor-using; bias' share in the total change in capital required over time in this case is quite large, representing some 34 and 54 percent in the 1920's to 1950's and 1950's to 1970's transitions, respectively.

The analysis of the relative impacts of efficiency and bias on changes in the quantity of capital (labor in the case of site preparation) is less straightforward due to their having opposing influences. The percentage increase in capital attributable to bias toward labor-saving in the 1920's to 1950's is some 1 to 39 percent in earthworks and 9 to 17 percent in surfacing; it is noticeably larger in the 1950's to 1970's, being some 13 to 50 percent in earthworks and 10 to 41 percent in surfacing. It was noted above that the trend in efficiency shares is just the opposite. Combining these two sets of data for capital gives the share of the decrease in capital due to efficiency which is lost due to bias' influence. This ranges from 2 to 56 percent in earthworks and 10 to 19 percent in surfacing for the 1920's to 1950's; for the 1950's to 1970's, the figures are notably larger, being, respectively, 32 to 131 percent and 24 to 207 percent. Along similar lines, when one compares the ratio of the percentage change in capital due to bias to that in labor, the figures for the two periods are about the same, ranging from less than 1 to 3.5 or so; the introduction of the appropriate capital/labor ratios, however, in order to ascertain the

cost, in terms of 1974 investment dollars, of bias' decreasing the number of men, shows significant differences. In the case of excavation/hauling at 100 meters, for example, it cost some 23,000 investment dollars in capital to decrease labor by one man in the 1920's to 1950's, while it cost some 100,000 investment dollars in the 1950's to 1970's. In summary, although the change in labor attributed to bias as a share of the total change in labor is about the same over the two periods, the cost, in terms of capital, of a unit of this bias, in terms of labor, in the 1950's to 1970's is significantly greater than that in the 1920's to 1950's, due to the higher capital/labor ratios; it is expected that the same trends might be observed in the case of site preparation, but with labor and capital switching roles, due to the lowering of capital/labor ratios over time.

Returning to the concern mentioned earlier, in conjunction with Figure 3.2, of overstating the magnitude of technology change and its effects, particularly with regard to the 1920's technology, it is useful to briefly consider the consequences of doubling the 1920's productivities and thus halving its quantities of men and investment. In Figure 3.3a, this is accomplished by simply a scale transformation, doubling it, and also bringing the 1920's packages down to the level of the new 100 percent; the effect on the percentage change in resource quantities due to efficiency is that it falls, while that due to bias doubles. The percentage change in labor attributed to efficiency as a share of the total change is still greater than that attributed to bias, with the same exceptions, site preparation and

excavation/hauling at 6 meters, as noted in the previous discussion of doubling the 1920's productivities. Furthermore, the cost, in terms of capital, of a unit of labor-saving bias remains the same since the capital/labor ratios do not change, although the share of the decrease in capital due to efficiency which is lost due to bias' influence increases. Nevertheless, with but a few exceptions, bias' role in changing resource quantities is still overshadowed by that of efficiency.

In summary, the impact of technology change on highway construction in the U.S. from the 1920's to the 1970's appears indeed to have been significant. Between the 1920's and 1950's, it offset, or even more than offset, inflation with prices of the factors involved, while between the 1950's and 1970's it kept cost increases down to a factor of two. Efficiency seems to have played a major role in this technology change, resulting in sizeable decreases in the amount of labor and capital required for highway construction, although the magnitude of these decreases has lessened over time. Substitution brought about by changes in factor prices, on the other hand, seems to have played effectively no role in the technology change observed. Bias appears as the non-neutral component of technology change, bias toward labor-saving, except in the case of site preparation where it is bias toward labor-using. Efficiency apparently accounts for some 80 to 95 percent of the drop in labor both from the 1920's to 1950's and 1950's to 1970's, while bias is responsible for only 5 to 20 percent. The cost of this labor-saving bias in terms of capital seems to have increased over time, however, due to increasing capital/labor ratios; in the 1950's to

1970's transition the impact of bias on capital is such as to completely overshadow that of efficiency in a few cases, while this is far from occurring in the 1920's to 1950's transition. As for the various stages of construction, it is noteworthy that the earthworks activities, especially excavation/hauling, appear to have a greater propensity toward capital intensity than do the surfacing activities, as exhibited by their larger capital/labor ratios.

4.13 Summary and Implications of the Results

Highways can be constructed in the U.S. today using significantly less labor and capital than was possible in the second and third decades of this century. These technology advances appear to have played a major part in keeping construction costs down, such that between the 1920's and 1950's the cost of the labor and capital in construction remained steady or even declined slightly, while between the 1950's and 1970's it about doubled.

This was accomplished between the 1920's and 1950's by means of increased mechanization and introduction of new types of equipment; that is, the hand and animal-powered, small capacity equipment of the 1920's, operated largely by unskilled labor with skilled labor acting in a supervisory role, was replaced by powered, larger capacity equipment, operated generally by skilled labor with occasional unskilled assistants, in the 1950's. Between the 1950's and 1970's, the means of accomplishment consisted of improving the equipment and the effectiveness with which it was used; that is, the equipment of the 1970's is largely similar to that of the 1950's except that it is

generally a little more powerful, larger in capacity, and more productive, although a few new types of equipment have been introduced as well.

In economic terms, efficiency appears to have played a major role in the technology change observed between the 1920's and 1970's, although the percentage decrease in resource quantities attributable to efficiency between the 1950's and 1970's is only about half that between the 1920's and 1950's. Efficiency appears to account for some 80 to 95 percent of the drop in labor required for most stages of highway construction, while bias toward labor-saving accounts for the remainder. Over time, however, such labor-saving bias has become increasingly costly in terms of capital, with increasing capital/labor ratios, and between the 1950's and 1970's, efficiency's reducing effect on the quantity of capital required has been overshadowed by bias' opposite impact in a few stages of construction. It might, at the same time, be noted that part of what is interpreted as bias toward labor-saving or capital-using may actually be due to the fact that production functions are not really continuous functions, but rather are made up of discrete technical packages; a certain amount of shift in the capital/labor ratio may thus be necessary to meet a legitimate technical package. Interestingly enough, substitution brought about by factor price changes seems to have effectively played no part in the technology change observed. Returns to scale are assumed to have been constant, although the observed changes in equipment capacity and coincident changes in project scale over time suggest this may not

truly be the case; it is thus suspected that some of the technology change attributed to efficiency may, in fact, actually be due to economies of scale, their separation posing an area for future investigation.

As for future expectations regarding technology change in U.S. highway construction, it is first useful to ascertain the motivations behind that of the past. The stability of demand in highway construction has likely been a primary factor, especially since the enactment of the highway trust fund in the fifties, although the market has always been rather steady as such construction is government-funded; this stability is a feature not shared by many sectors of the construction industry. Fairly stiff competition among equipment manufacturers and changes in highway design (e.g., standards and materials) and project scale have also undoubtedly motivated technology change. Although the increased cost of labor relative to capital cannot be cited as a direct motivation since no substitution was observed, it might be fair to say that expectations of such tended to induce technology change in the direction of increasing capital intensity. Moreover, it should be noted that it is primarily the equipment manufacturers who do the research, and it is to their obvious advantage to produce technical packages which utilize capital to the maximum extent possible.

As for the future, these same basic motivations are expected to continue, although some may be dampened a bit by an expected declining emphasis on highways, particularly on new construction, and increased emphasis on other modes of transport. Increased concern over energy and materials conservations is also expected to enter the picture. As

for means of accomplishing technology change in the future, a continuation of past trends of improving the equipment is expected, but perhaps even more important is improving the effectiveness with which it is used through better management, organization, and supervision, both on and off the project. It is important to note, however, that efficiency's impact on resource quantities was considerably less between the 1950's and 1970's than between the 1920's and 1950's, particularly in the case of surfacing, suggesting that future gains may be expected to be still less; moreover, labor-saving bias may be expected to become increasingly costly in terms of capital and to increasingly overshadow the effects of efficiency on capital. Advances in project design, particularly in the standardization of specifications and road designs and in the modification and use of existing or development and use of new materials, may be seen as potentially opening the door to further advances in equipment as well as moving toward conservation of materials. Important, too, is modifying existing or developing new equipment in order to reduce fuel requirements or enable it to use more available fuels; this is likely not compatible with the use of bigger, more powerful equipment in the future, re-emphasizing the importance of the effectiveness with which equipment is used. Future analyses of technology and its change in U.S. highway construction can no longer be limited to labor and capital as the primary factors of production, but rather materials and energy must also be included.

The characterization of technology change primarily in terms of efficiency and perhaps some economies of scale, but only a rather small

amount of bias and no substitution, appears to be a rather negative result in terms of developing countries' returning to the use of some of the older, more labor and animal-intensive technologies of the past. At the same time, however, it was observed that the 1920's technical packages formed a rather nice production function over a wide range of capital/labor ratios for most stages of highway construction, while those of the 1950's and 1970's largely fell along a single capital/labor ratio, resulting in right-angle production functions. Most importantly, an efficiency analysis over the production sets of all three periods also yielded a production function, although admittedly one with a large gap between the 1970's fully capital-intensive packages and the 1920's labor-intensive and animal-powered packages, with the latter likely arising as least cost only under rather extreme developing conditions such as those outlined in the research. It thus appears that the development of new technical packages since the 1920's has been focused on the capital-intensive end of the production function, where increased efficiency has indeed been achieved, and that the 1920's labor-intensive packages have essentially been forgotten, although they still appear as efficient.

In the case of some developing countries, it thus appears to be worthwhile for them to consider potentially using some of the more fully labor and animal-intensive packages of the 1920's, especially if they could improve the productivity; three frequently cited means include: (1) management, organization, and supervision; (2) tools and simple mechanical aids and the skills necessary to use them; and (3) general physical and social well-being of the workers. Moreover, the chances

of the 1920's packages in the overall efficient set appearing as least cost may be strengthened by consideration of mobilization and various other fixed costs associated with the large 1950's and 1970's equipment, particularly in light of the small scale projects common in developing countries.

In conjunction with these comments, some limited sensitivity testing is appropriate, the results of which are presented in Table 4.2. In terms of productivity, doubling the productivity of the light equipment (in order to test the magnitude of the effect) and using one-tenth as many supervisory personnel (resulting in about one per hundred unskilled men, as is perhaps more realistic in developing situations) have been tried; in terms of heavy equipment use, halving the annual utilization and doubling the maintenance as a percentage of investment cost have been tried (as these are perhaps more realistic figures when heavy equipment is used in developing countries). In the cases of doubling the productivity and halving the equipment utilization, a fully labor and animal-intensive package, the horse-drawn elevating grader and wagon (tp 8-7), show up in the 1920's least cost set at the prices of 1930, while the usual bulldozer (tp 7-6) shows up at the prices of 1974; in all cases, however, the 1970's elevating scraper (tp 8-11) is least cost overall. Substitution brought about by factor price changes has thus entered the picture of technology change over the period 1930 to 1974, suggesting that such circumstances could indeed have a significant impact on the economic feasibility of using certain of the 1920's labor and animal-intensive packages in developing countries today.

Table 4.2: Least-cost technical packages and their unit costs (dollars per 100 BCM) for excavation/hauling at 100 meters, for two technology and price periods, under various modifications of the productivity data and heavy equipment characteristics.

	1920's Technology		1970's Technology	
	1930 Prices	1974 Prices	1930 Prices	1974 Prices
1. Data as it stands	7-6 $10.3 9-7 $11.3	7-6 $63.1	8-11 $2.16	8-11 $14.8
2. Productivity modifications				
a. Double productivity of all light equipment, including associated men and horses	8-7 $6.75	7-6 $63.1	8-11 $2.16	8-11 $14.8
b. Use 1/10 as many supervisory personnel	7-6 $10.3 9-7 $11.2	7-6 $63.1	8-11 $2.16	8-11 $14.8
3. Heavy equipment modifications				
a. Halve hours used per year, leaving life in years the same, for all heavy equipment	9-7 $12.2 8-7 $13.5	7-6 $87.3	8-11 $3.48	8-11 $23.4
b. Double maintenance as a percentage of investment cost for all heavy equipment	7-6 $11.6 9-7 $11.7	7-6 $70.7	8-11 $2.68	8-11 $17.9

4.2 Interaction of Design and Technology in Highway Construction and Use

An investigation of the interaction of design and technology in highway construction and use involves the aggregation of the various stages, with their respective quantities, to the alternative projects and the evaluation of the quality of the final products. As noted in Section 2.32, the lack of production functions for the 1950's and 1970's and the existence of effectively right-angle production functions over the price range of 1930 to 1974 for each technology period alone and over all technology periods combined make the use of a production function-based aggregation procedure, as performed in the IBRD-I (42) and ILO-Iran (44) studies discussed in Section 2.21, unnecessary, as there is no choice of technical packages over this price range. As indicated in Table 3.10, then, the best-practice technical packages of the 1920's, the 1950's, and 1970's, as identified in the stage-level analysis, are used in the project-level analysis at the prices of 1930 and 1974. As there is, however, some choice of technical packages, at least among those of the 1920's and overall sets, if one is willing to go to more extreme pricing conditions, the project-level analysis is also carried out at the prices of a developing country today. As indicated in Table 3.10, the least-cost technical packages of the 1950's and 1970's at developing conditions are, not surprisingly, basically the same as those at 1930 and 1974 prices, while those of the 1920's and overall are vastly different. For the 1920's technology, the labor-intensive, animal-assisted technical packages are least-cost at developing conditions, while the

overall least-cost set is a mix of the 1920's and 1970's packages, the 1970's only taking over in the waterbound macadam and double bituminous surface treatment stages where fully labor and animal-intensive techniques were not even used in the 1920's.

4.21 Comparison of Alternative Projects

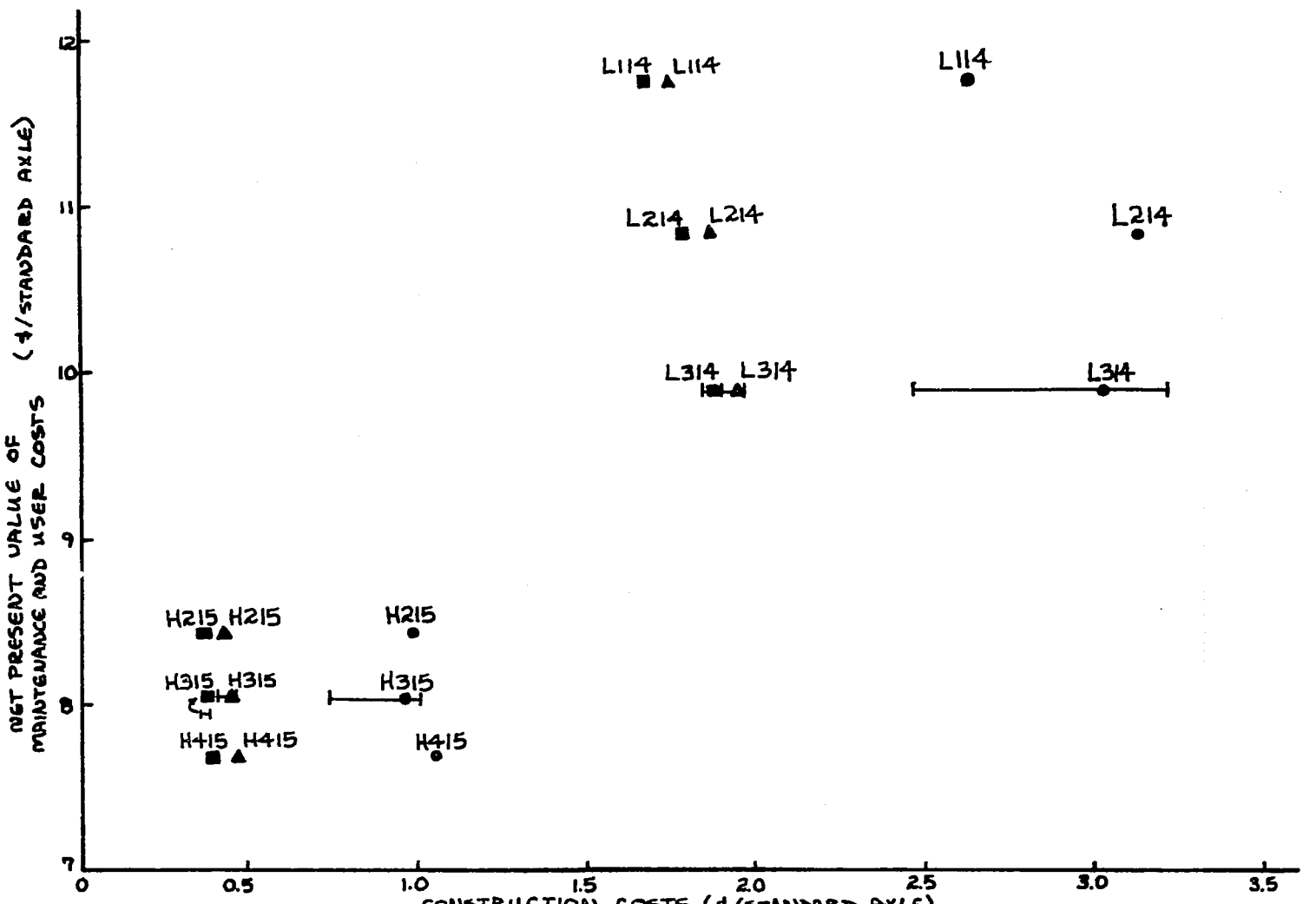
Given the project quantities (Table 3.9) and the least-cost technical packages with their unit costs (Tables 3.10 and B.5), the construction costs of the various projects (Table 3.8 and C.5) can be derived under various technology and price conditions. With construction costs as a measure of fixed inputs, or inputs now, to the project, maintenance and user costs, derived via the HCM and expressed in terms of equivalent annual costs, serve as a measure of largely variable inputs, or inputs over time, to the project. As the purpose of the road is to get someone from point A to point B and its life is taken as 15 years with its maintenance being such as to leave all projects in roughly the same condition at the end of that time, the only measure of output required is the volume of traffic the road is to carry over its life, most easily expressed in terms of cumulative standard axles; there are thus two levels of output, one tied to each set of design standards. Using this data then, production isoquants are developed as given in Figure 3.4, where each of the three groups of projects at each of the two design standards/traffic volumes must be analyzed separately.

Looking at the production isoquants for the two traffic volumes, certain economies of scale are evident in all cases; while the cumulative number of standard axles goes up by a factor of over 7.5, construction

costs rise by a factor of about 2 and equivalent annual maintenance and user costs by a factor on the order of 5 or 6. Moreover, a comparison of construction costs and maintenance and user costs on a cost per standard axle over project life basis, as given in Table C.5, for the two traffic volumes shows the unit costs to be significantly less for the high volume road in all cases. Similarly, plotting these unit costs, as in Figure 4.4, instead of the total costs, as in Figure 3.4, gives a single production isoquant for each project group in which the low volume projects appear to be inefficient. The implications of this are just what has been observed in the U.S., a trend toward building higher standard roads, although the traffic volume must be at least sufficient to offset the increased construction and likely maintenance costs.

As for the various project groups, the results are the same across all technology and price periods with the exception of the materials alternatives in the high standard/traffic volume case. Differences between the 1920's and the 1950's and 1970's technologies at 1974 prices can be explained by the overall low productivity of the 1920's technology in constructing a waterbound macadam surface (p H215). As for differences in the 1950's and 1970's technologies at 1930 and 1974 prices, these arise as a result of relative changes in materials prices over the period; that of bitumen rose by a factor of 5.0, while that of aggregate went up by one of 1.7. Under developing countries conditions, the double bituminous surface treatment over gravel road (p H315) falls out of the efficient set while the waterbound macadam road (p H215) enters it, again

Figure 4.4: Construction costs and maintenance and user costs, expressed in net present value terms, per standard axle over project life of each project/technology combination at each design standard/traffic volume, for all project groups and all technology periods, at the prices of 1974 (source: Table C.5).



(Figure 4.4 continued)

<u>Note</u>: Technology periods: ● 1920, ▲ 1950, ■ 1970.

|——| Indicates the range of construction costs of the alternative excavation/hauling scenarios, for a particular design standard and technology period.

largely as a result of relative changes in bitumen and aggregate prices. Waterbound macadam appears to fair rather poorly in terms of being an efficient alternative surface. It is felt that its construction costs may be overstated because of the compaction requirements placed upon it on the basis of 1920's descriptions of such road construction; at the same time, however, it is felt that its maintenance and user costs may be understated due to the use of a modified, surface treated road deterioration model. In the subgrade strength/surface design alternatives, the properly designed alternative on the weak subgrade (p L324, H325) is inefficient by definition, while the other two alternatives appear as efficient. As for the excavation/hauling scenarios, that with the shortest possible hauls (p L311, H312) comes out with the least construction costs and is thus most efficient.

The trends exhibited by the individual technical packages in terms of unit costs (see Tables 3.10 and B.5) are duplicated in the trends exhibited by the technologies in Figure 3.4 in terms of total construction costs. At the prices of 1930 and 1974, the 1970's technology has the lowest construction costs and is thus most efficient; also notable is the closeness of the 1950's costs to those of the 1970's relative to that of the 1920's and 1950's. Under developing conditions, the mix of 1920's and 1970's technologies is least in construction costs and thus most efficient, followed closely by the 1920's alone and more distantly by the 1970's and eventually 1950's. Underlying all of this, of course, is the assumption that each product is equal in quality regardless

of how it is constructed; if this is not the case, the tendency is generally to argue in support of greater capital intensity yielding better quality, at least in highway construction, thus strengthening the case for the 1970's technology.

Before trying to draw any further implications from this efficiency analysis, it is useful to look at the set of best-practice projects in each project group/design standard under various price and technology conditions, as presented in Table 3.11, in order to develop a feeling for the nature and magnitudes of the differences being observed. In line with the efficiency analysis, the best-practice projects are those which are least-cost, or within 10 percent of it, in terms of total project costs expressed as equivalent annual or net present values. Looking over the results in Table 3.11 reveals that, with the exception of the low standard materials and subgrade strength/surface design alternatives where at least two out of three projects end up in the least-cost set, all project alternatives in any project group fall into the best-practice set within any particular technology and price period. Moreover, looking across technologies in these groups leads to the observation that at 1930 and 1974 prices the 1950's technology always, and the 1920's better than half of the time, fall into the least-cost set along with the 1970's technology; at developing conditions, the 1920's technology always, and 1970's and 1950's technologies, often fall into the least-cost set along with the 1920-70 mix technology. A disaggregation of these costs into the partial construction, total construction, maintenance, and user cost

components, as given in Table 3.11, is necessary in order to see the dominance of various cost factors and to determine where differences among the projects and technologies lie.

Differences among projects are most evident at the level of maintenance costs and least at the level of user costs, while partial and total construction costs fall in between. On a total cost basis, the low standard/traffic volume design is significantly less than is the high standard/traffic volume design for all cost components except maybe maintenance, while on a cost per standard axle basis, the reverse is true for all cost items with some exceptions in partial construction costs; this is basically in accord with previous observations.

In the project group involving different surfacing materials, generally one or two projects are identified as least-cost at the level of partial construction costs; these are most frequently gravel (p L114) for the low standard, and double bituminous surface treatment over gravel (p H315) and waterbound macadam (p H215) for the high standard. The addition of surfacing materials in arriving at total construction costs generally has some impact, most commonly through the addition of projects to the least-cost set, thus expanding it, and less commonly through the replacement or deletion of projects in the least-cost set, thus changing it. As for maintenance and user costs, projects at the opposite end of the spectrum fall into the least-cost set; in the case of maintenance, for example, double bituminous surface treatment over gravel (p L314) and the same over waterbound macadam (p H415) are least-cost for the low

and high standard designs, respectively. It is the user costs which dominate total project costs, however. Only in the case of the 1920's technology at 1930 prices and in all cases at developing prices for the low standard design does the influence of low construction costs appear in the least-cost set under total project costs (i.e., p L114).

The situation is somewhat different in the group of subgrade strength/surface design alternatives. No distinction among projects is possible at the partial construction cost level, while the addition of surfacing materials to obtain total construction costs results in the deletion of the properly designed surface on the weak subgrade (p L324, H325). As for maintenance costs, the two sets of properly designed surfaces (p L314, L324; p H315, H325) exhibit the same costs and are least-cost, but at the level of user costs any distinction among projects is again impossible. As previously, user costs tend to dominate the total project costs, although in the case of the low standard project there is evidence of the influence of high construction costs in one case (at 1930 prices, L324 is not included in the final least-cost set) and of high maintenance costs in another (at developing prices, L334 is not included in the final least-cost set).

Finally, in the case of the various excavation/hauling scenarios, the situation is more like that in the first group of projects, although maintenance and user costs are constant across all projects at a single design standard. At the level of partial construction costs, generally only one project, that with the shortest set of haul distances (p L311,

H312), shows up as least-cost. The addition of surfacing materials, which are the same across all projects at one design standard, generally obscures any differences among projects, however. Maintenance and user costs complete the process for the few remaining cases where distinction is still possible.

Looking across the technologies in these three project groups for the various cost components shows basically that which is expected. At the prices of 1930 and 1974, the least-cost projects in terms of partial construction costs are those using the 1970's technology; in the case of total construction costs, the 1950's technology frequently enters the least-cost set along with the 1970's. Similarly, at the prices of a developing country, in the partial construction cost case the 1920-70 technology mix generally stands alone as least-cost, while in the total construction cost case the 1920's technology generally joins it. This progression continues until, as noted above, in the total project cost case it is not uncommon for all technologies to end up in the least-cost set.

In order to gain some feeling for the relative magnitudes of these various cost components as well as their change over time in the U.S. and for the rather overshadowing influence of materials and user costs, various cost data are plotted for a road at each design standard in Figure 3.5. Much as observed in the stage-level analysis, technology change in highway construction between the 1920's and 1970's seems to have nearly offset the coincident inflation in labor and capital prices, as

indicated by the graph of partial construction costs. At the total construction cost level, assuming no change in materials usage, technology change appears to have been instrumental in keeping cost increases between 1930 and 1974 down to a factor of about 1.7; this is somewhat less than the cost increase observed for materials over that period, and about half of what construction cost increases would have been had technology not changed. The cost-reducing influence of technology change in highway construction appears to be rather diminished at the total project cost level due to the magnitude of user costs, the technology of which along with that of maintenance is assumed constant at today's. Project cost increases on the order of 3.5 are exhibited between the 1920's and 1970's, notably less than those in maintenance and user costs but only slightly less than those expected had technology not changed. Had the 1950's and 1970's technologies similarly been compared at 1956 and 1974, it is expected that the diminishing role of technology change would be more evident at the total construction cost level, due to the relative magnitudes of materials and partial construction costs.

At this point it is appropriate to look at some of the components comprising these various cost items. As expected, labor's share of partial construction costs decreases while capital's increases with the progression in technology; moreover, labor's share in the high standard project is somewhat less than in the low standard one, primarily as a result of the large amount of earthwork required in the high standard design, activities which are highly capital-intensive. Nevertheless, labor's

share looks somewhat low relative to capital's, with the exception of the 1920's technology at 1974 prices. A possible explanation is that expenses for labor beyond the basic wage and fringe benefits (e.g., social security [FICA], workmen's compensation insurance, and unemployment, amounting to about 15 percent in 1974 [54]) are included in overhead and profit, although mobilization costs for equipment are also included there, rather than directly with the labor and capital costs, respectively.

Proceeding to examine total construction costs, the cost of labor and capital relative to that of materials appears to be too small, with the exception of the 1920's technology at 1974 prices. A number of factors account for labor and capital's share being too low; these include: (1) the figures represent the best-practice technical packages for each period, selected under the assumption that the project at hand is part of a larger project, and there is thus no constraint as to minimum period of use of any package on the project or need for coordination of packages among activities (using an average-practice technical package in the case of excavation/hauling in the 1970's, for example, might increase the unit cost of the package by a factor of less than 2 to over 3 depending upon the haul distance); (2) as indicated above, additional expenses associated with labor, as well as mobilization and any other fixed costs associated with capital, are included in overhead and profit, which is expressed as a percentage of all direct costs, although it might be more appropriate, at least for overhead associated directly with labor

and capital, to express it as a percentage of the labor and capital costs and to include it with them (especially in light of the fact that a charge for transport costs to the site is included in the cost of materials); and (3) in the case of the low standard road at least, there is very little earthwork, which is where the sizable labor and capital requirements appear, and thus the project is largely surfacing, which is oriented more toward materials than toward labor and capital.

The share of materials in total construction costs may appear to be high for a few additional reasons, as follows: (1) the quantity of surfacing materials required is rather sizable, especially that of gravel due to the rather low subgrade strength (e.g., p L114 requires 29.2 centimeters [11.5 inches] of gravel and p H315 requires 33.0 centimeters [13.0 inches]); and (2) the surfacing materials, particularly the aggregate, may be higher quality than is necessary for road construction and may thus be overpriced, as data on materials is largely for building, not heavy, construction (e.g., aggregate is often given in conjunction with concrete, suggesting it is probably cleaner and more accurately sized than is necessary for many highway projects). Finally, minor structures are not included in the construction costs, and these could be expected to augment both labor and capital costs and materials costs.

Looking at the bar graphs of total project costs, the magnitude of user costs relative to other project costs is evident, and as expected, is somewhat greater in the high standard design with the higher traffic volume. Maintenance costs are, as expected, significantly less than

construction costs, and both represent a smaller share of the costs in the high standard/traffic volume project. Finally, several of the comments made above would serve to augment construction's part in overall project costs.

4.22 Summary and Implications of the Results

The efficiency analysis yields the following results: (1) the apparent existence of economies of scale among projects for various traffic volumes; (2) an indication of the efficient surfacing materials alternatives (generally all except waterbound macadam [p L214, H215] which appears in the high standard case when bitumen is expensive), efficient subgrade strength/surface design alternatives (all but the one which is properly designed on a weak subgrade [p L324, H325]), and efficient excavation/hauling scenarios (that with the shortest set of hauls [p L311, H312]); and (3) an indication of the overall efficient technologies under various price conditions (1970's at 1930 and 1974 and 1920-70 mix at developing). The significance of these results becomes questionable, however, when the results of the least-cost analysis show all projects, or at least two out of three, to be within 10 percent of each other in total project costs. Similarly, for a particular project group/design standard, all technologies or at least two of them are found in the overall least-cost set.

Upon disaggregating the total project costs to their various components, distinctions among projects again become evident, most clearly at the level of maintenance costs and least so at the level of user costs;

this latter cost item generally dominates the outcome at the total project cost level with only an occasional influence from the construction or maintenance cost level. Moreover, the technologies also regain their distinction, with one technology (1970's at 1930 and 1974; 1920-70 mix at developing) showing up in the overall least-cost set at partial construction costs, and two (1970's and 1950's at 1930 and 1974; 1920-70 mix and 1920's at developing) at total construction costs. Such disaggregation, however, does little to help in the analysis of project alternatives where materials, maintenance, and user costs vary, as in the case of two of the project groups under study. An incremental analysis, such as that given as an example in Table 4.3, where the overall least-cost project/technology combination at 1974 prices (i.e., L314 at 1970 and H415 at 1970) is used as a base to be subtracted from the other projects in the group, sheds little further insight into the problem. Although sizable cost differences and greater distinctions seem to appear among the various projects and technologies, their significance is questionable; that is, many of the incremental costs, at the more aggregate and user cost levels in particular, represent only a small share of their respective total costs, an observation in accord with that of insensitivity in the full cost analysis in Table 3.11.

It is apparent, nevertheless, that the cost-reducing influence of technology change in highway construction on project costs is indeed significant. At the disaggregate level of partial construction costs, for example, technology change between the 1920's and 1970's appears to

Table 4.3: Incremental costs (in $1000), over the base case at each design standard, of each project/technology combination, for all surface materials alternatives and all technology periods, at the prices of 1974, for the various cost components (source: Table C.5).

Design Standard/ Technology Period/ Project	Construction Costs		Operation Costs[b]		Total Project Costs[b]
	Partial[a]	Total	Maintenance	User	
Low Standard Design					
Base Case					
1970-L314	32.9	501	199	2416	3116
Incremental Values					
1920-L114	+206	+195	+58	+443	+696
-L214	+305	+327	+114	+139	+580
-L314	+251	+302	0	0	+302
1950-L114	+8.2	-43	+58	+443	+458
-L214	+27.2	-7	+114	+139	+246
-L314	+12.7	+16	0	0	+16
1970-L114	-2.7	-56	+58	+443	+445
-L214	+10.8	-26	+114	+139	+227
High Standard Design					
Base Case					
1970-H415	138	789	187	15171	16147
Incremental Values					
1920-H215	+1024	+1179	+250	+1260	+2689
-H315	+950	+1133	+125	+604	+1862
-H415	+1083	+1300	0	0	+1300
1950-H215	+94	+63	+250	+1260	+1573
-H315	+75	+82	+125	+604	+811
-H415	+100	+121	0	0	+121
1970-H215	-4	-55	+250	+1260	+1455
-H315	-18	-29	+125	+604	+700

Note: The base case is the overall least-cost project/technology combination at 1974 prices and is subtracted from the other combinations to give the incremental values.

[a]Include cost of labor and capital used in construction, although site preparation materials (≤4% of this cost item) are also included in the few cases where they are used.

[b]Expressed in net present value terms, the discount rate being 8%.

essentially offset inflation in factor prices. Upon aggregation in the direction of total project costs, however, other factors come into view, materials and user costs in particular. In order to study the overall impact of technology change on highway construction and use in the U.S., be the technology change via the technical packages of construction, materials usage, maintenance policies and procedures, or transport technology, studies similar to the one at hand are first needed in these other areas as well; the results of the construction-based study are reasonably encouraging, at least in terms of past trends. Knowledge of the trends of the past as well as the expectations for the future in all of these areas in the U.S. is of importance. As noted in the stage-level analysis, the modification and use of existing or development and use of new materials, for example, is seen as necessary for future advances in the area of equipment as well as in that of materials conservation. The role of user costs in total project costs is such as to warrant major studies in the area of transport technology and its development; important, too, is the development of more sensitive models for measuring user costs. Finally, future studies should involve a broader set of projects and eliminate some of the shortcomings and limitations of the current study such as explicit consideration of mobilization costs and project size.

On a somewhat different note, a few comments remain to be made about the implications of this analysis for developing countries. The results, in terms of alternative construction methods, certainly do look promising.

That is, under developing conditions, admittedly rather extreme ones, the 1920's fully labor-intensive, animal-powered packages do appear as least-cost for all stages except waterbound macadam surfacing and double bituminous surface treatment. Further testing is certainly needed, however, with regard to the range of economic conditions under which this occurs. As noted in the stage-level analysis, the case is potentially strengthened by consideration of possible productivity improvements and inclusion of mobilization and other fixed costs associated with heavy equipment. It should further be noted, however, that as in the U.S. situation, research is also needed in the areas of materials usage, maintenance policies and technology, and, probably most importantly, transport technology, if project costs are to be minimized.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Conclusions

The role of technology in the productivity of highway construction over the years in the U.S. appears indeed to have been a significant one. Highways can be constructed today using considerably less labor and even less capital than was possible in the second and third decades of this century. These advances in highway construction technology appear to have played a major part in keeping project costs down, essentially offsetting, or more than offsetting, inflation in the prices of labor and capital between the 1920's and 1950's, and keeping labor and capital cost increases down to a factor of two between the 1950's and 1970's; it should, at the same time, however, be noted that at the level of total project costs, the cost-reducing influence of such technology change tends to be overshadowed by other cost components, user costs being most dominant.

Efficiency seems to have played a major role in the observed technology change, although the magnitude and rate of the decrease in resource requirements attributable to efficiency has lessened over time. For most stages of highway construction, efficiency appears to be responsible for some 80 to 95 percent of the drop in labor required, with bias toward labor-saving accounting for the remainder. This labor-saving bias, however, has become increasingly costly in terms of capital, to the point of overshadowing efficiency's reducing effect on the

capital requirements in a few stages of construction. Part of what is interpreted as bias may, in fact, be due to the discrete, as opposed to continuous, nature of production functions. As for substitution brought about by factor price changes, it seems to have had effectively no part in the technology change observed. Constant returns to scale are assumed, but it is suspected that some of the technology change attributed to efficiency may, in fact, be due to economies of scale, in light of the coincident changes in equipment capacity and project scale over time.

Increased mechanization and introduction of new types of equipment appear to constitute the primary means of accomplishment of such technology change between the 1920's and 1950's in the U.S., while between the 1950's and 1970's it is largely just improving the equipment and the effectiveness with which it is used. A primary motivation in all of this has likely been the stability of the market in highway construction, a government-funded operation. Reasonably stiff competition among equipment manufacturers, along with changes in highway design and project scale and some standardization of design features, in part a result of the interstate program, has also undoubtedly motivated technology change. As for its being in the direction of increasing capital intensity, it should be remembered that it is primarily the equipment manufacturers who do the research; it also seems likely that expectations of labor's cost rising relative to that of capital have tended to induce technology change in the direction of saving labor although no substitution was observed.

As for the future, these same basic motivations are expected to

continue, although some switching of emphasis toward the repair and upgrading of highways, as opposed to new construction, and toward other modes of transportation may dampen some of them a bit. Energy and materials conservation is also expected to be of increasing interest. As for means of accomplishing technology change in the future, a continuation of past trends of improving the equipment and, more importantly, improving the effectiveness with which it is used is expected. Research in materials and standardization of specifications and road designs among other advances in project design may assist in the advancement of equipment as well as in the conservation of materials. Research in the area of fuel conservation and use of alternative fuels in relation to equipment use is also of importance; the likely incompatibility of using bigger, more powerful equipment and conserving fuel in the future reemphasizes the importance of the effectiveness with which equipment is used.

It has thus been observed in the course of this research that gains in both labor and capital productivity and efficiency in highway construction over the years in the U.S. have been substantial, resulting in certain offsetting of factor price increases. Nevertheless, if trends of the past are indicative of the future and a continuation of past means of accomplishing technology change is to continue as the primary means in the future, then gains in efficiency can be expected to be less than those previously, and labor-saving bias to become increasingly costly and to increasingly overshadow efficiency's effects on capital. This means that labor productivity will increase at a slowed rate, while the

productivity of capital will increasingly tend to decline. In line with this, productivity's effectiveness in offsetting factor price increases may be expected to continue to fall. At the same time, the somewhat inexplicable substitution of labor by capital may be expected to continue. This suggests that new means of accomplishing technology change in highway construction need to be investigated; moreover, the motivation and meaning of labor-saving bias in the industry ought to be looked into, in order to ascertain its desirability from the viewpoint of all involved.

As for the developing countries, the results of the study, at first glance, appear to be rather negative in terms of the wisdom of their returning to the use of some of the more labor-intensive, animal-powered technologies of the past, in that technology change in highway construction in the U.S. appears to be primarily characterized by efficiency and perhaps some economies of scale, but only a relatively small amount of bias and no substitution. At the same time, however, it was observed that an efficiency analysis over the technical packages of all three periods results in production functions for most stages of construction, ones largely made up of the 1970's fully capital-intensive packages and the 1920's fully labor and animal-intensive packages, with just a couple from the 1950's. Moreover, under the developing conditions outlined in the study, admittedly rather extreme ones, the 1920's packages arise as least cost for all stages except the two higher standard surfaces. The development of technical packages since the 1920's thus seems to have been focused on the capital-intensive end of the production

function, where increased efficiency has indeed been achieved; the 1920's labor-intensive packages seem to have been essentially forgotten, although they still appear to be efficient and, under some conditions, economic. It does, therefore, appear to be worthwhile for at least some developing countries to consider potentially using some of the more fully labor and animal-intensive packages of the 1920's, particularly in light of, for example, possible productivity improvements, inclusion of mobilization and other fixed costs associated with heavy equipment, and application of more realistic utilization rates for developing conditions.

5.2 Recommendations for Further Research

The first recommendation for further research is a more in-depth analysis of the means and motivations behind technology change in highway construction in the U.S., past, present, and future. The current research provides greater understanding of the nature and magnitude of technology change over the past fifty years or so; a component, which is still lacking, however, and which is so necessary in guiding the future direction of technology change, is greater insight into why this change occurred — what were the underlying motivations. Moreover, as observed above, the means of accomplishing technology change in the past do not look very promising for the future, and therefore, new approaches to improving resource utilization need to be investigated. Finally too, certain characteristics of the technology change that has been observed, such as the labor-saving bias, are puzzling and need further analysis in terms, for example, of what has motivated them, who benefits,

and should such trends be encouraged or discouraged in the future.

A second recommendation is testing and, as appropriate, reducing some of the restrictions in the current research in future studies. Restrictions limiting the general applicability of the results lie, for example, in the assumption of "typical" institutional and environmental conditions and in the limited number of alternative surfaces, designs, and projects investigated. Omission of certain activities, such as minor and major structures and materials production and transport, constitutes another area. A third area of restrictions, and perhaps the most important, is that of simplifying assumptions, such as full utilization of equipment, balancing of additional labor and capital costs above the basic hourly rate and their inclusion in general overhead and profit, constant returns to scale, generally uniform product quality and time to produce a given output across technical packages (excepting, of course, specification of 93 versus 98 percent earthwork compaction and various surfacing materials), and each project's being a part of a larger project thereby being able to use only best-practice technical packages and having no need for coordination of packages. Several of these assumptions relate in one way or another to project scale, an aspect of highway construction definitely warranting further consideration; economies of scale, for example, are felt to be in part, at least, responsible for some of the technology change attributed to efficiency. The feasibility of further analysis of many of these restrictions rests on the availability of data, which is a problem in that historical data often fails to be sufficiently detailed.

A third recommendation is that studies of materials usage, maintenance policies and procedures, and transport technology and their change over time in highway construction and operation in the U.S. be made; the impact of this overall technology change might then be better understood, with the results of this study of the technical packages of construction being reasonably encouraging, at least in terms of past trends. Knowledge of past trends and future expectations is of importance in all of these areas. The modification and use of existing or development and use of new surfacing materials, for example, is perceived to be necessary for further advances in equipment as well as in materials conservation. User costs constitute such a major share of total project costs that studies in the area of transport technology and its development are clearly warranted; also important is the expansion of the data base pertaining to the estimation of road surface deterioration and the impact of design standards and surface conditions on road user costs, making more feasible the development of more sensitive models for measuring user costs.

Investigation of the role of technology in other sectors of the construction industry in the U.S. and elsewhere and its influence on productivity and efficiency and product quality and cost constitutes the fourth recommendation for further research. This is of importance in terms of indicating the direction of technology advance in the past and its potential in the future in these sectors in the U.S. and other developed countries; in the case of developing countries, it is of use in terms of assessing the potential appropriateness of various technical

packages. Other areas of heavy construction provide some interesting possibilities for research; in the case of tunneling, for example, the main thrust of technology change has occurred more recently, with research in the area potentially guiding its future path. Building construction is also of interest, particularly in light of the criticism it receives for being slow to adopt advances in technology. The study of technology and productivity in this sector of construction, even narrowing the scope to a single type of building like federal office buildings, is more complex, however, due to the large number of steps in the construction process and difficulties in the measurement of output in quantity, quality, and use terms.

The fifth and final recommendation pertains to developing countries and the additional testing and evaluation of the implications of the research at hand for the developing situation. First and foremost is further testing with regard to the range of economic conditions under which the more labor-intensive technical packages of the 1920's appear to be economic. At the same time it is appropriate to try to alleviate some of the more relevant and restrictive limitations, omissions, and simplifying assumptions discussed under the second recommendation. In view of the small scale projects common in developing countries, for example, explicit inclusion of mobilization and other fixed costs associated with heavy equipment as well as more realistic utilization rates for such equipment seems appropriate; such adjustments would, of course, tend to strengthen the case supporting the use of the 1920's technical packages. Also of importance is investigation of alternative

means of improving productivity, perhaps via management, organization, and supervision, tools and simple mechanical aids and the skills necessary to use them, and general physical and social well-being of the workers; in a couple of the case studies reviewed in Section 2.21 (e.g., IBRD-III [38,39,40] and ILO-Philippines [43]), field studies and demonstration projects are successfully used in the development, testing, and implementation of such measures to improve labor productivity. In line with recommendation three above, further study is also needed in the areas of materials usage, maintenance policies and technology, and, probably most importantly, transport technology in the developing countries, if project costs are to be minimized. Of interest, too, as noted at various points throughout the study, is the potential for labor-capital substitution in maintenance, materials production, and major and minor structures construction.

APPENDIX A

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