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Transportation Services and Innovation in the Housing Industry: A Study of the Relations between Transportation and Production

by

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Abstract

Innovations improve the organization of production and provide new products and services. While it is accepted that economies are stimulated by innovations, the role of transportation improvement in stimulating innovation has not been sufficiently examined. This role is examined in this study. A methodology for examination of the contribution of transportation improvements to production is presented. Residential housing construction is chosen as the sector of production for study. This sector is large and important, is generally considered to be experiencing reduced or negative productivity growth, and is transportation intensive. This thesis begins with an analysis of conventional productivity studies. These studies fall short in their attempts to explain productivity changes. An examination of the long history of housing construction reveals that productivity changes have resulted from the adoption of innovations, innovations enabled by improvements in transportation.

Following a discussion of innovation theory, a list of housing innovations and a typology for their classification is presented. From the list, drywall construction is chosen as for case study.

To provide a temporal frame for the analysis of housing technology, provide time series data on growth and change, and explore simple relationships, trends in transportation and housing productivity are presented and examined. These data characterize transportation systems as mature and productivity in housing as stagnating.

Investigation of the specific relations between transportation improvement and housing productivity change is the subject of the last section of the thesis. The savings enabled by the adoption of the drywall construction innovation are estimated. The calculation of savings is based on estimates of innovation adoption rates and saturation levels assuming the truck-highway system had not been deployed. Using this approach, the benefit of truck highways through this single innovation is found to be on the order of

fourteen percent of truck related road costs.

Acknowledgements

1 Introduction

The relations between transportation and production are the concern of this research. These relations are known in a general fashion. For instance, tightly scheduled transportation service enables just-in-time manufacturing. This study, however, seeks to go beyond simple generalizations. It investigates the processes that link transportation improvements to changes in other sectors. The processes unfold over time, so dynamics are involved. The dynamics unfold in nonlinear ways -- ways not well understood.

To cut through complexities and to assist in exploring a range of ideas, the relations between transportation and the construction of residential housing are taken as a case at point. As will be seen as the research is presented, the path from transportation improvements to changes in production steers through innovation processes and productivity gains from innovations. For this reason, the study bears on innovation and productivity changes -- large topics.

The objective of the study is to nail down relations. Its broad goal is more global: to illuminate some of the ways transportation enables innovations and the progress of the economy.

The purpose of this chapter is to explain the motivation for this research, to clarify the objective and scope of this study, to define the research methodology, and, finally, to distinguish this research from conventional lines of work.

1.1 Motivation

Much effort has been devoted to identifying the causes of productivity changes. We share the interest in explaining these changes, and sense that relations between transportation and productivity, (and thus, trends in economic development) are stronger than are currently recognized. Motivated to "prove" that point, we have taken a step toward exploring it.

Timely opportunities also motivate this research, opportunities that transportation improvements might open. Some say we approach a period when the world economy may be headed for another great stagnation (see Mensch, 1979; Kondratieff, 1984; Snyder, 1981). That we are in a period of slow growth can not be denied. Renewed gains in industrial productivity are possible. However, recollection of the last economic depres-

sion and recovery prompts asking whether things will get worse before they get any better. A deeper understanding of the causes of productivity change is called for, particularly those causes heretofore unidentified.

In his critique of traditional economic analysis (referring to the economics preoccupied with the normative operations of firms) Schumpeter wrote in *Capitalism, Socialism and Democracy*:

> "The competition that counts is competition from the new commodity, the new technology, the new source of supply, the new type of organization - competition which commands a decisive cost or quality advantage and which strikes not at the margins of the profits and the outputs of the existing firms, but at their foundations and their very lives. This kind of competition is as much more effective than the other as a bombardment is in comparison with forcing a door, and so much more important that it becomes a matter of comparative indifference whether competition in the ordinary sense functions more or less promptly; the powerful lever that in the long run expands output and brings down prices is in any case made of other stuff." (Schumpeter, 1942)

Schumpeter has not gone unheeded. It is accepted that economies are stimulated by innovation. What stimulates/enables innovation? We think the role of transportation has not been sufficiently examined.

Hence this study has been motivated to examine this role, to identify the relationships between transportation and production, and to recommend transportation policies benefiting productivity. More specifically, the objective for this research is presented in the following section.

1.2 Objective

The objective of this dissertation is to develop an understanding of a process; we seek understandings of how transportation affects the organization and efficiency of production. In particular, we will analyze and explain the relations between transportation developments and productivity gains in the residential housing construction sector. Ultimately, we make statements about the way in which these relations may be studied for other sectors.

This research treats rarely (if ever) analyzed processes. Hence, there is sparse previous work on which to build. Thus, one product of this research is conceptual and methodological: How should the relationships between transportation and production be studied? Beyond that, this research sets out to identify relations between transportation and production, to quantify these relations, and finally to make recommendations for transportation directions based on the relations.

1.3 Scope

Our interests are in the relations between transportation and production. However, the scale of this effort necessarily limits us to the study of a manageable unit of production. This section describes the rationale for choosing the housing production sector as this unit.

Residential housing construction was chosen as the sector of production for study. This sector is large and important, generally considered to be experiencing reduced or negative productivity growth, and transportation intensive. It's big; nationally, about 30 percent of personal income is spent on housing costs (including operations). It's in trouble. There is much concern over sectors of the economy which do not seem to be gaining productivity. One of these sectors is construction, and in particular, construction of residential housing. Although there is some disagreement in the literature over measurement of productivity in residential construction (hereafter, also referred to as housing productivity), it is widely noted that this is an industry plagued by low productivity growth.

Direct transportation input to residential construction is given by national input-output studies to be only about 5 percent (USDOL, 1980). However, nearly all facets of construction depend on the transport of labor and materials, as the organization of housing production turns on transportation. Some housing supply industries such as lumber production report up to 70 percent of their costs to be direct transportation costs (UNIDO, 1984/85).

The residential construction sector posted significant productivity gains during the middle part of the last and the first part of this century. These gains and the lack of recent gains appear to be transportation related. The gains (or lack thereof) coincide with deployment and maturing of the rail and auto-highway systems. There is a clearly

observed correlation (Aschauer, 1989), but what are the underlying relationships causing this correlation? Does transportation development lead or lag changes in production; by how much?

In spite of gross correlations and transportation intensity, transportation issues are not found in the literature of housing productivity. Chief issues are standards and building codes, seasonality, stagnant technologies, financing, and high materials and labor costs.

1.4   Research Methodology and Outline

While it is not a traditional productivity analysis, this study examines factors and underlying relationships affecting or enabling productivity change. Even so, Chapter 2, "Productivity Analysis and the Housing Industry," provides an introduction to productivity analysis in general and specifically as it applies to the housing industry. Special attention is given to limitations of conventional productivity analysis in showing the strong relations between transportation and production. Based in part on the examination of these limitations in Chapter 2, this research goes on in a rather Schumpeterian fashion to present innovation, in particular, innovation enabled by transportation improvement, as the proximate cause of productivity change in housing.

Chapter 3, "A Long View of Housing and Transportation," presents a historical summary of the housing construction industry. Attention is focused on qualitative relations between transportation and housing production.   The chapter provides a context and meaningful time frame for examination of changes in housing innovation technologies. Chapter 3 also supports our contention that traditional productivity analysis is scoped to too short a time scale for identification of some factors (chiefly innovations) effecting productivity change.

Chapter 4, "Innovation in the Housing Industry," draws on previous work in product-cycle theory and the concept of economic long waves.   After providing background for the long wave concept, a section is presented describing the forms of housing innovations. We employ a classification terminology developed by Gerhard Mensch that places innovations within the concept of product life cycle.

Examination of a list of housing innovations suggests two additional classification levels: impact of innovation, and arrangement of causality for the relations between transportation and production.

Using "form of innovation", "type of innovation impact", and "arrangement of causality" as headings, a typology for classification of housing innovation is developed. The typology can be used to generalize results of analysis for specific innovations to similar innovations as well as to other classes of innovations.

As our general objective is to improve understandings of the relations between transportation and production, Chapter 5, "Housing and Transportation Trends," presents trend data on transportation and construction, emphasizing housing. Its purpose is to provide a temporal frame for the analysis of housing technology, provide time series data on growth and change, and explore simple relationships between housing and transportation trends.

Chapter 5 is organized in three major parts. First, transportation data are presented. In general, these data reflect S-shaped trends in transportation system deployment. (Chapter 4, "Innovation in the Housing Industry," discusses the use of S-shaped curves in analysis.) The second section provides time series data for the construction industry. Data specifically for housing construction were obtained where possible. However, due to reporting methods and scope of coverage, building data were sometimes more comprehensive than housing data. In the third and last section, trend comparisons are presented to indicate the extent to which transportation and housing production trends correspond.

In Chapter 5, the conclusions to be drawn from the comparisons of transportation and housing trends include some supported by (roughly) direct correspondence and others that require interpretations that go beyond direct, simple comparison. To facilitate comparison, and to place transportation systems within the life cycle framework, simple logistic growth models were fit to some of the transportation data.

In Chapters 4 and 5, we view the broad relations between transportation improvement and production in the housing construction sector. This sweeping view does not permit examination of the impact of transportation on the specific details of production. Chapter 6, "Case Study: Drywall Construction," narrows the focus. We identify a par-

ticular innovation in housing construction and trace its development, seeking a better understanding of the role of transportation.

In Chapter 6, the reasons for selecting drywall construction for case study are presented. After a brief discussion of the history of drywall construction, we model the substitution of wallboard for plaster using a logistic equation. The relations between transportation system development and housing production are analyzed using the substitution as a case in point. Trends identified in the Chapter 5 which reflect improvements in passenger (labor) and freight (building material) transportation are correlated with the adoption of the drywall construction innovation. A discussion of industrial location presents an example of the impact of transportation system development on the spatial organization of production. Finally, we calculate the benefit of drywall to residential construction. By estimating the influence of truck transportation on the substitution of wallboard for plaster, we are able to approximate the savings to residential housing production enabled by the marginal improvement in transportation services from rail to truck.

It's easy to say that without modern transportation, we would have a near subsistence economy. That is irrelevant. What's important are the changes that can be made at the margin of present systems. If we choose to make improvements of a marginal nature, benefits will be just that, marginal. Building from that observation, Chapter 7 concludes the dissertation with a discussion of what can be done to produce improvements, changes creating new paths of transportation system development and marked improvements in production.

1.5   On Conventional and Nonconventional Work

Conventional transportation analysis and subsequent investment decisions are usually based on limited information. Broad impacts of investment are omitted from analyses; only transportation criteria are used to justify transportation investments. Measures on attributes of speed, time savings, capacity, frequency, comfort, and operating cost enter typical decision making.

For example, decisions to build or expand existing urban freeways turn on expected costs (construction, operations, maintenance, right-of-way, legal ...) and benefits (time

savings, lower vehicle operating costs, local development, ...). Some consideration is given to incidental or externality costs, usually negative externalities, such as noise.

In contrast to this practice, to paraphrase the French civil engineer/economist Jules DuPuit, the objective of improvements in (transport) systems should not be to reduce the cost of transportation, rather, to reduce the cost of supply (production) [DuPuit, 1844]. In the spirit of DuPuit, we seek to identify the measures that should receive priority. These measures should reflect how transportation organizes production by:

- improving uses of old resources (lowers cost, waste, ...)

- making new resources available
- expanding the scopes of markets (this allows economies of scale and specialization)
- expanding labor sheds (producers can draw from a better pool of labor, picking the best)
- providing new consumption choices (consumers have more variety and can shop, fosters competition)
- enabling agglomerations of production activities (reduces inefficiency, waste, and duplication)
- and broadly, stimulate and permit innovations that are the engine of economic change

The research reported in this thesis is unconventional in its focus on relationships such as those listed above. As the text approached listing those relationships, use was made of the word *measures*. That was to emphasize that we would ultimately seek to replace the measures conventionally used with measures related to the development consequences of transportation investment. Our research is toward that ultimate. Although suggested by DuPuit, that, too, is unconventional.

It's important to choose the right measures for transportation investment decision making; such decisions are characteristically expensive and long lasting. Robert Louis Stevenson wrote:

"Our road is not built to last a thousand years, yet in a sense it is. When a road is built, it is a strange thing how it collects traffic; how, every year as it goes on, more and more people are found to walk thereon, and others are raised up to perpetuate it, and keep it alive; so that perhaps even this road of ours may, from reparation to reparation, continue to exist and be useful hundreds and hundreds of years after we are mingled in the dust."
(National Automobile Chamber of Commerce, 1921)

Specifications are often locked into system developments in the early stages of deployment to meet temporary goals (processes are irreversible). Once standards have been set, it is difficult if not impossible to reverse their course.

1.6   References

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2 Productivity Analysis and the Housing Industry

While this research does not include a traditional productivity analysis, it gives much attention to factors directly affecting or enabling productivity change. For this reason and because this research may broaden concepts brought to productivity analysis, this chapter provides an introduction to productivity analysis in general, and specifically as it applies to the housing industry.

2.1 Productivity - A Measure of Production Efficiency

The growth of productivity in a society is essential to the well being of its economy. Simply put, productivity improvements reduce the real cost of products consumed. They reduce inflation pressures and help industries control costs when meeting increased demands. There are a broad range of concepts and interpretations bearing on productivity, as we shall see in the forthcoming sections.

2.1.1 Definition of Productivity

Productivity is commonly defined as the amount of real output per unit of input or inputs. Because the goods and services produced across an economy have inputs and outputs that are generally measured by a wide variety of units, productivity measures vary across sectors. So for comparisons, global productivity measurements use general units, typically dollars (for output, or capital) or hours worked (for labor inputs). An appropriate specification of the definition of productivity is essential to its proper use as an analytical tool, especially when temporal or cross-industry analysis is desired.

2.1.2 Productivity Measures

There are two traditional methods of productivity measurement. The first is single factor productivity, where a ratio is taken between total output and one of the inputs needed to manufacture or produce a product or service. A broader, and often more meaningful measure is total factor productivity (TFP), also known as overall productivity, or simply productivity or performance. This is the ratio of output to all inputs. While TFP may be more meaningful, single factor productivity is easier to compute and is sometimes desired, especially when one of the inputs is of paramount importance to the analyst.

In many industries, productivity is measured as real output per unit of work. Work units are often specified as hours worked or hours paid. An inadequacy of this measure is its inability to represent the effects of substitution of capital for labor.

Measurement of a homogeneous output is simple: number of cans, bales of hay, etc., however, few outputs are homogeneous and money is often used as an aggregate measure of output (i.e. sales, production). Quality of product is not directly represented by cost or price. However, quality may be represented at least indirectly by the price. In addition, monetary values must be deflated. The correct application of price and cost indices is a subject of much debate.

The meaningful measurement of productivity is further complicated by the existence of intangibles such as the effect of production on the environment (externalities), equity or aesthetics. The quantification of output is particularly difficult in the case of the production of goods or services which are not sold, as in government functions, charity operations, or construction of public facilities (Stein, 1971). Three sectors where measurement of output is especially complex are government, service, and construction. For construction, in particular, output measures may not be comparable in coverage to input measures (Mark, 1971).

As for inputs, the quality, not just the amount of labor required is relevant. Pay differential is sometimes used as a proxy for quality, but other factors influencing pay differences should be accounted for if possible. Other problems include data gaps, and that the hours paid in a firm are not usually equal to the number of hours worked.

The amount of money spent on capital may be used to estimate the capital input, but variations of quality of equipment has prompted the use of average age of equipment as an estimate of quality. The age, however, is still inadequate where new technology in machines produces improvements and relatively new equipment is quickly rendered obsolete. Two measures are used to represent the amount of capital used in an industry: gross capital and net capital. Gross capital is the total amount of money spent on capital averaged over some time period or amount of output. Net capital is capital depreciated, although tax laws affect true measures of depreciation. Depreciation is referred to as a "flow" measure, as it measures the amount of capital used per time period (Mark, 1971).

Probably the biggest constraint to accurate productivity measure lies in the availability of data. Because productivity measurement is rarely the purpose for collection of industry data, the data rarely appear in the form most suitable for analysis. Often, substitute measures must be used.

2.2 Difficulty in Analyzing Housing

Construction in the United States is conducted by a complex network of 480,000 firms. Of these, 290,000 specialize in one form of construction or another, and 130,000 classify themselves as residential builders (Construction, 1988). "Residential building is made up of so many hundreds of thousands of mostly small-volume builders, carpenters, sub-contractors, real estate persons, and many other workers, that it is difficult for anyone to control, organize, or even understand its intricacies." (Mason, 1982) Mason notes that housing construction takes place in over 20,000 towns and communities and many more scattered locations in the rural and suburban U.S., each with its own local codes, zoning, environmental demands, distribution methods, and servicing requirements. He concluded that the vast dispersion had discouraged large-scale production and that houses could not be turned out like "autos from Detroit" because each piece of land (building site) was an individual problem relating to terrain, utilities, local codes, and customs. In addition, little if any distinction is made between residential and other construction activities in the available data. Because of its size and dispersion, statistics on the building industry are widespread and not necessarily consistent.

One source identified four problems with the technical assessment of housing. They are: 1) difficulty in accounting for quality changes, 2) inconsistency in definition of inputs, 3) variations in the mix of off and on-site activities, and 4) difficulty in disaggregating construction into residential and non-residential sectors. These problems do not permit a refined (traditional) analysis of productivity in residential construction (Quigley, 1982).

2.3 Conventional Concepts

On examination of conventional productivity assessment, it is noted that assessment is generally limited to static analysis, that is, productivity studies are typically scoped in time such that changes in organization of the sector of study are not incorporated.

Examples include the Bureau of Labor Statistics (BLS) studies from the late 1940's to the present. (See the Appendix for Chapter 3.)

To facilitate the observation of variations in productivity over economic long-cycles, a long time frame for analysis is required (50 years or more).[1] Traditional productivity studies look at only a portion of one of these cycles. If one begins observing productivity on the upswing of a cycle and stops during the late stages of a cycle where gains are marginal at best, one should expect to see a decrease in the rate of productivity growth.

Schumpeter noted that the competition that makes a difference (in real productivity gains) is competition in the introduction of new products, ideas, and services. With a few exceptions (i.e. Solow's Nobel winning work) technological change has not figured prominently into traditional economic productivity analysis. Although most economists acknowledge the contributions of technological change, several factors are involved in keeping technological change out of conventional economic analyses. Ignorance of natural science and technology on the part of economists, their preoccupation with trade cycle and employment problems, and the lack of suitable statistics are some of the factors. In addition, most economists are committed to accepted assumptions and systems of thought. These conventions, ceteris paribus for example, relegate technological change to the realm of "exogenous variable." And although more recently, econometric studies attribute the larger portion of growth to technical progress, technological change remains at the fringe rather than at the center of economic analysis. (See Freeman, 1982)

Many building sector innovations are enabled by transportation improvements. Both materials and resource supply and the organization of labor depend on transportation. A long look at the history of housing production shows that many of the time and money saving innovations have been enabled by improvements in transport methods (see Chapter 3).

This dissertation hypothesizes that cycles in productivity change in the building sector are closely related to cycles in the deployment of transportation systems. It also

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[1]See Chapter 4 for a discussion of long cycles in economic analysis. These cycles or "waves" have been observed to have a period of 50 years or so.

introduces transportation as a factor in productivity assessment, beyond analysis of direct transportation inputs to construction within a traditional static technology frame.

2.3.1 Measures of Productivity

We wish to identify causes of productivity change in the housing industry, in order to isolate those involving transportation. Productivity gains occur either as a result of changes in technology, or as a result of some other reason, such as learning, during periods of relatively stable technology. We wish to distinguish between these. However, Hooper (1987) points out that it is questionable whether "simplistic methods are capable of comprehending complex production relationships." As an alternative to the "simplistic" methods, this reference presents some econometric estimations of productivity indices for the transportation industry. Productivity may also be analyzed by first specifying appropriate production functions. Parametric testing may then be used to study of productivity change. Derivatives may be taken to analyze rates of change with respect to time. This method places large requirements on tools and data (Hooper, 1987).

2.3.2 Productivity Growth

Productivity as measured by the ratio of output to inputs can grow in several ways (output can increase faster than inputs, output can stay the same while inputs are reduced, etc.). Growth measures can be classified hence into four categories: those that increase total output, those that decrease total input, those that do both, or those that produce the desired effect of increasing productivity by increasing the ratio of outputs to inputs by improving one more than the other. An example extension of the first case would be a change in transportation technology that sacrifices speed for capacity improvements thereby improving the output for a particular purpose (such as the transport of housing).

Some factors that influence general productivity growth have been outlined in (Arai, 1979). They are:
1) government policies for expansion,
2) capital investment,
3) technological innovation,
4) long range policies,
5) education,
6) skills and ethics,
7) quality control,
8) labor-management relations,
9) economies of scale, and

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10) systems improvements.

The Building Research Advisory Board (BRAB) has identified some areas for action concerning the improvement of construction productivity. These areas, which are equally pertinent to other sectors of the economy are (BRAB, 1979):

1) management,
2) financial planning,
3) government and public action,
4) human motivation, and
5) innovation.

Some policies which may tend to restore productivity growth have been identified (U.S. President, 1980):

1) provide investment stimulus,
2) support research and development,
3) increase government productivity,
4) encourage cooperative efforts between firms,
5) emphasize long run decisions (by use of the regulatory environment), and
6) increase productivity and quality of work life programs (labor/management cooperation).

2.3.3 Productivity Trends

The annual growth of productivity of all industries in the United States from 1950 to 1970 has been estimated at three percent (Stein, 1971). After 1970, that rate has decreased. Reasons for this deterioration have been given as:

1) slower growth of capital stock relative to labor,
2) reductions in transfers of labor out of the less productive agricultural industry,
3) increased regulation,
4) demographics (a small effect),
5) higher energy costs, and
6) reduced innovation. (U.S. President, 1980)

It is important to distinguish between productivity rate and productivity growth rate. Although the U.S. productivity growth rate has declined, the productivity rate remains among the highest in the world. Declines in some rates such as labor productivity may be qualified. For example, the substitution of labor for energy after the OPEC embargo has led to a decline in, or at least a slowdown in the growth rate of single factor (labor) productivity, while a total factor analysis would result in an increase. In this case, TFP may be more appropriate.

2.4 Sector Productivity

The following sections narrow our focus to productivity in transportation and housing.

2.4.1   Productivity in Transportation

Various measures of productivity are commonly used in the analysis of different transportation modes. For example, total factor productivity in the airline industry is usually taken as the ratio of an aggregate of output (e.g. passenger-miles, freight ton-miles) to an aggregate of inputs (i.e. labor, fuel, equipment, capital, commissions, operating overhead). A common single factor measure of highway productivity is vehicle miles travelled (VMT) per mile of road.

From 1950 to 1970, transportation productivity increased at an average yearly rate of 3.3 percent (Stein, 1971). Recently, a decline in transportation productivity growth rate has been observed. Some constraints to the increase of productivity have been identified. They are declining markets (as is the case for public transit), increased competition (which reduces scale economies, but which also may improve operations efficiency), and higher energy costs.

Transportation productivity improves with the introduction of technological innovations as well as with increasing demand which allows the capture of scale economies. Of course, increasing demand for a fixed facility (plant) exhibits increasing returns only to the point where congestion or maintenance becomes a problem.

This research looks into the causes of the reduction in transportation productivity. Chapter 5 places the current auto-highway system in the concept of product life cycle and explains reduced gains in transportation productivity as a phenomenon of maturing systems. While transportation productivity has been studied, conventional analytical techniques rarely if ever include the concepts of life-cycle and long-waves employed in this study (see Chapters 4 and 5).

2.4.2   Productivity in Housing

Reasons given for the recent lack of housing productivity gains include restrictive building codes, unfavorable financial markets, seasonality, low investment in basic research and development, high cost of labor and materials, restrictive labor practices, and

others. However, these issues fail to account for a significant portion of the productivity slowdown experienced in the last two decades.

Accurate measures of productivity in the construction industry are difficult to obtain for many reasons, including: the large size of the industry, inadequacies of price deflation methods, varying and imprecise units of work (output), the diffusion of the industry, and the fact that there is no index for land prices which account for approximately 25 percent of housing prices.

Even when data for construction productivity can be compiled, traditional or conventional measures such as the level of capitalization and the amount of value added can be misleading. These measures, while they may be appropriate for other more stable industries, may not be as applicable to an industry described as "dispersed, diverse, discontinuous, and detached." (Dowall, 1986) The industry is dispersed due to an uneven distribution of labor, materials and demand, diverse as represented by tens or even hundreds of thousands of firms, discontinuous due to seasonal variations of the weather, materials and demand, and detached due to the characteristics of work movement patterns, short term or specialty arrangements, and shifts from one material or component supplier to another (Dowall, 1986).

Measures of factors and outputs commonly used to calculate construction productivity are the following: 1) number of full and part-time employees, 2) hours worked by full and part-time employees, 3) hours paid (all employees), 4) hours paid (all persons), 5) employment (all employees), 6) employment (all persons), 7) value of housing starts, and 8) value added per employee (Stokes, 1981).

2.5   Housing Productivity Constraints

Some constraints to construction productivity have been listed as: immobility, geographic dispersion, many independent specialized segments, business cycles which lead to rapid turnover, and low research and development expenditures (Peck, 1979).

A portion of the apparent slowdown in the growth of construction productivity might be also be explained by the policies and actions of trade unions. "It has been traditionally held that they (unions) resist the introduction of new techniques which would tend to speed up productivity - how much a man produces per hour." (Arnold and White,

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1960) However, this does little to explain the recent productivity losses, especially since the era of increased union influence passed before the recent construction slowdown. In fact, unions were particularly strong during periods of productivity growth.

Although many people agree that there has been a recent decline in the productivity of the construction industry, there is no consensus for the reasons for this decline. Much of the data used to analyze productivity are in aggregate form, and the question to be asked is "how the inputs of capital, labor, and technology combine to affect output." (Construction, 1988)

Another concern regarding the productivity of the construction sector is the lack of emphasis on research and development. There are several reasons for this lack of emphasis. Important questions are: "What should be the general level of research?" and, "Should the research be directed toward finding short run marginal productivity improvements, or should it foster the development of basic innovations which would lead to large gains in the magnitude of productivity?" (Construction, 1988)

Because output is not clearly defined, productivity in construction is difficult to measure. That is, one may define output to be the number of, or square footage of buildings produced, but quality of the final product is not easily quantified. There are no comprehensive criteria for measuring the quality of construction output. Structures must meet building code requirements, but these requirements focus on quality of components rather than quality of the finished product (Construction, 1988).

2.6 Strategies for Improvement of Housing Productivity

Two commonly mentioned stimuli with the potential to improve (increase) housing production are to lower interest rates (some fear that extending the money supply to do this would cause inflation, but there are ways to control that), or to increase federal subsidy of housing (which declined from 20 billion in 1982 to 10.6 billion in 1983 to 4.1 billion in 1984, est. [U.S. Senate, 1983][2]). General productivity areas include: investment, materials, land, and labor. Productivity waste occurs with regulation, poor labor practices, poor management, and capital losses during construction (Peck, 1979).

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[2]These figures do not include mortgage deduction tax subsidies.

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Manufactured housing has been looked toward for the next round of housing productivity gains. Japan's housing industry has achieved phenomenal productivity advances in the recent past by improving industrialized housing concepts.

Transportation technology improvements have enabled housing productivity gains in the past. These gains can be observed as new transportation technologies have permitted changes in housing construction methods and the supply of materials. (See Chapter 3, "A Long View of Housing and Transportation.")

2.7 Housing Productivity Trends

Recently, there has been a marked decline in the rate of construction productivity. One report states that between 1948 and 1965, construction productivity increased at a robust rate of 3.4 percent per year. However, for the 1970's and 1980's, productivity had actually declined at a rate of 1.8 percent per year - a net difference of 5.2 percent (Construction, 1988). Another source reported a gain of 2.4 percent per year for the years 1950-1968 and a decline of 2.8 percent per year between 1968 and 1978 for a net decline of 5.2 percent (Stokes, 1981). Speculation as to the causes of this decline led to research described in Stokes (1981) where 7 possible reasons were identified. These seven: 1) errors in measurement of real output, 2) shifts in the composition of output, 3) decline in the amount of capital invested per worker, 4 and 5) demographic changes (age, sex), 6) regional shifts, and 7) changes in work rules and practices, however, were found to account for less than one-third of the decline.

Productivity gains experienced during the years from 1920 to 1950 were likely induced by both market and technological forces. This was the era of initial investment in federal highways and public works programs. These investments provided a market large enough for construction firms to realize returns to scale. During this period, there were major advances in machinery which replaced both human and animal labor.

Further productivity gains were enabled during the period of the 1950's and 1960's by the introduction of machines with higher capacities and power, together with the great influx of capital afforded by the interstate and toll roads programs (Construction, 1988). Since 1970, there has been little investment of either capital or innovation which would produce the types of gains experienced in earlier years.

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Reasons given for the decline in productivity include higher building costs, international competition, changing demand patterns, and the unique structure of the industry and its functional characteristics (Construction, 1988). However, some of these "causes" may be "effects" of decreased productivity.

In one study, a 0.2 percent annual decline in productivity of the construction industry was contrasted with Bureau of Labor Statistics reports for various sectors which showed, for example, a 2.75 percent per year gain in school construction productivity, and a 3 percent gain per year in the productivity of hospital construction (Mark, 1971).

It is unlikely that one, uniform quantitative measure of housing productivity could be identified for use over the entire time span of interest to this study. Transportation improvements which have enabled housing productivity gains through reorganization of production have occurred over three centuries beginning with canal development, continuing with railroad deployment, and ending with the auto/truck highway system. The availability of data constrains conventional analysis to much shorter time frames (necessary for specification of homogeneous measures).

2.8   Motivation for an Unconventional Analysis

The results of conventional productivity analyses are interesting. They identify a crisis in housing and construction, and they identify some of the causes of productivity decline. However, the causes they identify are topical. The failure of productivity analyses to account for a large residual (unexplained causes) motivates an unconventional approach. Conventional analyses are careful to identify direct inputs to housing production, those inputs for a given (static) technology. A dynamic concept with measures reflecting organization of production (labor organization and the supply of materials) is the approach taken in this research. Transportation enters as the set of services enabling the organization of this production.

It has been the objective of this chapter to present a brief introduction to conventional productivity analysis as it applies to transportation and housing. We have identified a problem (reduced productivity in residential construction), and we have made remarks on our study. Our study bears on the direct transportation inputs to housing and on innovations that have and might drive productivity improvements.

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3 A Long View of Housing and Transportation

3.1 Introduction

One objective of this study is to identify the aspects of housing production which would likely benefit from improvements in transportation technology. Historical identification of housing inputs is the central theme of this chapter. Both of the direct inputs to housing - capital (including materials, financing, land, and overhead) and labor - are greatly impacted by transportation efficiency.

Technologies (or processes), are not considered as inputs. Rather, they define the way in which capital and labor are combined to produce output. As will be seen, some important building technologies turn on transportation services. While one may easily quantify the portions of capital, labor, and process costs attributable to transportation, this study has a different goal: to identify the changes in building technology, housing materials, and labor organization which have been enabled by transportation systems improvements.

Land is considered by some to be the most important non-financial resource for housing, comprising 20 to 25 percent of the total sales price for most single-family housing (Solomon, 1975). Transportation has impacted the price and availability of land: Settlers came to the Americas in ships, the railroad opened up western parts of the U.S., and the automobile greatly increased the amount of land usable for residential construction around cities. However, as the scope of this research is limited to the study of production, land use considerations are not addressed.

Further, due to limitations of data and references and to the intended application of the findings, the scope of this chapter is limited to the housing industries of Northern Europe (mainly Great Britain) and to the United States.

We are interested in a long frame of reference for this study. This is important as a study of a short (40 years or less) period does not permit the consideration of Schumpeterian changes in production. The objective of this chapter is to present an overview of a long history of the production of housing. This overview sets the context and provides the necessary background for the quantitative analysis presented in subsequent chapters. Some of the developments examined in this chapter have no direct bearing on the relations between transportation and housing production. However, taking a

sweeping look at a comprehensive range of historical developments facilitates the identification of relationships which might otherwise be overlooked.

3.2   Specialization of Labor

Long ago, civilizations were organized around agriculture. Housing was constructed by local labor using local building materials. Scale economies were limited to local specialization of labor (the local carpenter built locally). Because of the bulky, heavy, low value-per-unit characteristics of building materials, the status of transportation constrained the types and quantity of building materials available.

The advantages of labor specialization were discovered early on. Labor specialized and trades were formed. People started to rely on others to do jobs that previously had to be done by every family, if not every person. Some people hunted better than others. Others would cook, clean, build, take care of children, grow food, fish, practice medicine, make tools and weapons, make and repair clothing, entertain, etc. Each community had at least one person to perform each of the tasks of life. Economies were gained as individuals learned from experience and could focus their energies on specific tasks. Skills were learned and passed on from generation to generation.

3.3   Housing Inputs to 1750

Housing inputs before the mid-eighteenth century were generally restricted to local labor and, except for a small percentage of very expensive items in well-to-do homes (such as fine marble or glass windows), mainly local building materials.

Buildings in stone or brick were relatively rare prior to the Middle Ages. The high cost of transportation and fuel prohibited the use of masonry in all but the most expensive structures such as cathedrals, monuments and fortresses.

"Because of the difficulty and slowness of communications the cost of transport of building materials was serious, and frequently much higher than the total paid to the quarrymen. Stone used at Eton College in the fifteenth century was worth about a shilling a load, but a further 6s 6d had to be added to this after its journey by road, sea, and canal from Huddlestone to Yorkshire. As a result, first, local stone was used where available, and secondly, as much preliminary mason's work as possible was performed at the quarry. In this way quarries became mason's nurseries, where mastery over less elaborate work was attained." (Singer, 1956)

The organization of many western building trades originated in medieval Europe. Since medieval times, construction labor has been divided by craft - the roots of modern unions. It was then that a system was created where apprentices learned from journeymen who in turn were employed by master craftsmen. Under the master mason were the freemason and the rough mason. Each of these artisans employed laborers to carry and heave (Singer, 1956).

The carpenter worked alongside the mason on stone buildings. His job was to build scaffolding and supports for arches to be used until placement of the keystone.

Although it is said that building underwent no industrial revolution, (most innovations, e.g. cast iron, Portland cement, were used only on large projects) the organizational structure of the industry did. Building changed from structures being built by tradesmen, to contractors employing tradesmen, to builders (architects, merchants, etc.) hiring contractors, to master builders providing permanent employment to tradesmen (Burnett, 1986). However, in the pre-industrial era, these organized builders constructed mostly urban structures and before indoor plumbing or household electricity, carpentry and perhaps masonry were the only two trades involved in building a house. Typically, early houses were built by local, non-specialized labor with a carpenter or the home owner himself doing all the work from the ground up.

Changes in the types of building materials and styles used occurred due to factors other than transportation improvements, such as the expansion of the use of brick and stone after the great fires and plagues of London around 1660 (Arnold and White, 1960), or because of the innovation of new tools (the water powered saw to mill boards out of timber).

The main point of relevance to be drawn from the above history of pre-industrial revolution building is that housing quality and productivity were severely limited by very expensive or non-existent transportation systems. Not only were builders restricted to the use of local building materials, but to those local materials which could easily be worked by the craftsman (Condit, 1968). Materials which were more difficult to work with such as metals or stone were not extensively used for housing in many locations. Pegs were substituted for nails, clay and straw for mortar, and wood for stone.

3.4   Early Maritime Transportation

Long ago, transportation needs were extended beyond that of personal and tribal mobility. Information has long been a priority commodity for transportation. Royal decrees and lesser mails were carried by teams of foot messengers, swift animals, or by ship. These methods were capable of delivering information at speeds of up to 300 km per day. "Ancient empires never became larger than an area allowing 15-day mail service from the capital." (Marchetti, 1988) Freight and passenger transportation, however, was extremely slow and inefficient relative to today's. Heavy freight was chiefly transported over water.

Efficient freight (and passenger) transport by sea is a relatively recent phenomena. Ocean-going used to be limited to sight of land. Several innovations allowed travel out of sight of land (the astrolabe and sextant facilitated both more direct travel and travel to unexplored or remote lands). Although after these innovations it was possible to navigate to most points on the globe, transport was slow (depending on wind and weather conditions) and costly (due in part to breakage and spoilage of cargo, as well as to disease and death of passengers and crew). The impact of shipping on housing before the deployment of inland waterways was therefore minimal. Construction materials carried by ship were limited to those for major public works or monuments, although occasionally stone and bricks used for housing construction were carried as ballast.

It was the advent of inland water transportation that allowed some economical movement of heavy, non-local building materials (such as stone and bricks), as well as the transport of coal (used to fire bricks) [Burnett, 1986]. Canals, the first efficient form of inland freight transportation, afforded the first widespread use of non-local building

materials. The importance of canals was reduced after the introduction of the railroads. In his book *Railways and American Economic Growth*, Robert Fogel estimated benefits of railroad deployment (Fogel, 1964). He compared transportation costs between railroads and canals. He did not include opportunity costs associated with transportation enabled changes in production. This method of conventional analysis is critiqued at a later point in this thesis.

3.5 Housing and the Industrial Revolution

An early impact of the industrial revolution was the production of machines which greatly increased productivity, required factory production, and, with market growth, the demand for labor. There was migration from rural agricultural areas to cities. This migration placed a heavy burden on housing in the growing urban areas.

Transportation was required to get agricultural products off the farm and to the cities, and to get machinery and manufactured goods from the cities to the farm. The supply of fuel (firewood and coal) and other raw materials found in remote areas and needed in the cities demanded improved transport methods.

Cities quickly depleted locally available building materials, and new, efficient forms of transportation were required to get these low value per unit items from the mines and forests to the cities.

Three basic changes in the building industry during and after the industrial revolution (the 18th and 19th centuries) greatly affected the organization of building labor. They were: labor unionization, improvements in transportation, and improvements in machinery.

3.5.1 Labor Unions

The formation of unions characterized the reorganization of building after the industrial revolution. Construction labor unions retained some of the early characteristics of medieval guilds such as apprentice, journeyman, and steward roles and agreements that only certain craftsmen can produce certain work.

Unionization may be said to have changed the structure of labor. However, it may also be said that unionization was a result of these changes. Carpentry, the largest of the building trades, provides a good case for study.

Carpentry unions were not needed in early America. Before the eighteenth century, carpenters were independent tradesmen who would travel from town to town looking for work. Due to lack of competition, they generally set their own prices, and decided which jobs to take and how to do them.

This lack of competition can be attributed to poor transportation and communications systems; carpenters who were underemployed or who might be willing or able to do the job "better" had neither the information nor means of transport necessary to compete for the work. During this period, the carpenter generally built the entire house from local materials. He felled the lumber, cut it into beams or boards, and then built with these materials. There was insufficient means of transportation to ship either raw or finished building materials; only the most expensive or necessary items warranted costly transport (Christie, 1956).

As colonial towns grew in size, there was growth of transportation, commerce, and financial systems; building labor specialized. The work previously performed by the carpenter alone was split up to form three occupations: lumberjack, sawmill hand, and house builder (Christie, 1956). Carpenters no longer chose to fell their own lumber, and better forms of transportation (water and rail) enabled transport of logs from forest areas to the locations where water could be used to power "up and down" saw mills, and then to locations of housing demand. It was then that the old world system of apprentice, journeyman, and master returned. Competition increased, wage rates were reduced, more work was demanded of the laborer; the environment was right for union formation (Christie, 1956).

The carpenters' union dates from 1724 with the organization of the Carpenters' Company, a masters' protective organization. The Bricklayers Company was formed in 1790. Organization of unions was at first very difficult, as common law prescribed penalties for conspiracy for members of groups organized to improve working conditions or increase pay. At first, unions provided the worker an arena for socialization then later, benefits, such as death benefits.

The first incidence of subcontracting is attributed to the Carpenters' Company as master carpenters sublet jobs to journeymen for four-fifths of the contract price. Originally, construction work was contracted piecemeal. For example, bricklayers were

paid $2.75 per thousand bricks laid in 1831 (on buildings of less than three stories). A days work was from dawn to dusk (over 15 hours in the summer).

In 1791, the carpenters association formed into city wide journeymen's trade unions. Also in 1791 the carpenters struck for and won a ten hour work day. The same was won by stonecutters as the result of a strike in 1823. In 1825, the stonecutter's struck for a $2.00 per day wage (Bates, 1955). Formal national unions were founded in 1850 for the bricklayers and plasterers, and in 1881 for the carpenters. Through the 1880's carpenters were a single craft union. However, with the change of building technology (specialization) carpenters were divided into many trades in the first twenty-five years of the union. By 1940 the union's jurisdiction included over two pages of trades in its constitution (Christie, 1956).

Although some carpenters were more highly specialized than their eighteenth century counterparts, many jobs still required a great breadth of knowledge through at least the 1940's. The carpenter working to build the traditional "stick built" house often had to possess a breadth of knowledge comparable to the architect or job engineer. With increasing industrialization, and prefabrication and pre-cutting of materials, in many instances today, this breadth is no longer required, and has been replaced by specialization for efficiency and scale economies.

One major effect of unions on the organization of labor can be summed up in the following quotation: "...(there is) work carpenters have always done and are entitled to do." (Christie, 1956) This traditionalist's philosophy is a constraint to industrialization and other changes in the building industry.

3.5.2   Transport Improvements

Improvements in transport methods during the 1800's impacted the organization of housing production. Railroads made it possible for tradesmen to travel to labor markets in locations which were previously beyond a reasonable commute. By the 1850's, competition arose between workers in widely separated cities. By the Civil War, unions were state-wide in organization.

Prior to the industrial revolution, carpenters did all of the finish work on site. During bad weather, the carpenter fashioned windows, doors and frames, posts, cabinets,

and other finish work inside the building or in a carpenters' shack. Transport improvements enabled off-site fabrication of many of these components. Later sections of this text discuss transportation relations in more detail.

3.5.3   Machine Improvements

During the late 1700's, a third development, woodworking machine innovations, dramatically changed the organization of building labor. These innovation replaced on-site labor and greatly reduced the cost of items such as blinds, mantel brackets, doors, ceilings, flooring, windows, and stairs. Typically, there was a large reduction in labor costs for these components. Unskilled laborers, many of them women and children, replaced the labor of dozens of carpenters. Those carpenters still needed were reduced to installers at half the wages of fully trained carpenters. Specialization brought about a division of carpentry into many trades such as door hangers, floor layers, stair builders, etc. Installation work was particularly suited for the old piecework method of payment. After these developments, carpenters united to form a national union.

3.6   Pre-Railroad Housing Inputs

Houses were constructed of mostly local materials in Colonial America and Europe before the introduction of rail transportation. Both transportation constraints and cultural traditions helped to make wood the general preference of Colonial builders. During the early periods of American colonization, as a result of laws designed to reduce the likelihood and damage of disastrous urban fires, English authorities required that homes be built of brick. However, as brick was not widely produced and because a transportation system was not yet in place that could economically carry low value, high weight material over long distances, many wood frame houses were constructed. Houses were constructed of wood despite Southern settler's preference for masonry houses resembling those of their native England (Williams, 1976a). Stones were used if they could be easily obtained in the local area. Clay suitable for brickmaking was plentiful, but was not utilized until an area became economically prosperous enough to afford the fuel to fire it (Condit, 1968). The first brick house in the Colonies appeared in 1654 in Virginia, but brick construction was not extensively used until around 1700 when increased wealth and better forms of transportation were obtained (Williams, 1976a).

Exclusively local materials were used in housing construction in other parts of the U.S. In the Southwest, adobe buildings were manufactured using clays and bits of straw, manure or brick. In the lower Mississippi valley, crude structures of heavy timber were built, and in many areas, settlers learned to use the building materials and imitate or improve upon the building methods of the Native Americans.

3.7   Railroads and Residential Construction

Early locomotives had little speed or capacity advantage over animal power, and originally substituted in limited markets for coal wagons conventionally pulled by horses or mules. But, as technology improved in the 1840's, the railroad found many market niches. Mineral ores and heavy building materials were early rail freight commodities as were passengers and manufactured goods.

3.7.1   The Railroad and Housing Demand

The railroad opened up vast new expanses of land for development. New farm and ranch lands were made available as products could be shipped to densely populated areas fast enough to prevent spoilage. No longer were cities constrained to navigable waters.

During the early and rapid growth years of railroad deployment, rural populations increased as new territories were opened and demand for food for the burgeoning cities grew. For a time, there was a large demand for rural housing, but this trend was soon replaced by rural emigration as farms became more productive and jobs became available in urban areas.

During the first three-fourths of the nineteenth century, urban areas in the U.S. depleted local material resources. Space in urban areas was limited, because commute methods (walking, horse and buggy) constrained the practical radius around industry where workers could live. The demand for housing called for taller buildings. New housing construction methods were required to prevent overcrowding and slums.

Even in urban areas with lesser space constraints, the depletion of local materials became a problem. A good example is Chicago in 1830's. A shortage of large timbers, used in traditional braced frame housing, limited the supply of new housing. Conditions were right for innovation of a new method of construction, balloon framing.

Prior to 1830, the method of construction for most American houses was timber or "braced frame." This labor intensive method was characterized by heavy, hand-hewn timbers required for sills and posts connected with mortise and tenon joints and secured by wooden pegs. Braced frames were covered with water-proof clapboards.

In 1832, balloon framing, the first "stick-built" method, was introduced by Chicago builder G. W. Snow. (The method was first used in the construction of a church by a carpenter, Augustine Taylor [Fitch, 1973]). This method utilizes a lightweight wood frame as the load bearing structure for the roof and the upper floor (if present). Snow developed balloon framing to take advantage of structural designs which provided a stronger but lighter weight and much easier to build structure. Two developments requisite to the feasibility of balloon framing were affordable, machine made wire nails (introduced around 1830) and standardized precut, lightweight lumber (made available by the railroad). Standard sized lumber was economically transported by the expanding railroads and scale economies were realized as lumber cutting operations could be moved to central locations near the supply of raw materials.

Balloon framing was introduced at least in part to meet the increased demand for housing where wood was plentiful but carpenters were not. Together with transportation improvements, timbers could be cut, marked, and numbered at the saw mill and shipped ready to use to the site, thereby saving much on-site labor (Singer, 1956).

Originally necessitated by high transportation costs of materials, balloon framing went on to capture most of the Nation's housing market and replace other methods. This innovative construction concept enabled modern methods of prefabrication (which date back to the Illinois Cottage sent to the Paris Exhibition in 1867) and led to the development of Western Framing, a similar but improved method of building one story at a time (Jandl, 1983).

Western (one story at a time) framing, the chief "stick-built" method of today, uses standard length boards that capture economies in production and transportation.

An additional consequence of balloon framing was the open interior plan where wings of a house could be built around a central utility core which provides three exposures for all rooms (Condit, 1960).

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Rural situations divide into two types. The first had access to a plentiful supply of local building materials. There, demand for transportation of building materials was less than that of urban areas. However, labor was non-specialized and more scarce. The carpenter was the only tradesman. House-building skills were the common knowledge of any man on the farm. Methods of construction were limited to those which could be accomplished using hand-tools. The housing product was unrefined and emphasized necessities rather than comforts.

In the second category, rural housing had little access to local building materials. Examples are the great plains areas of the U.S. There was little wood for either building lumber or fuel to fire bricks. Houses were often built out of straw and mud or manure. Transportation was demanded to take farm products to market and return processed and manufactured goods as well as building materials and fuel.

3.7.2   The Railroad and Housing Supply

Construction materials were the first of housing's inputs to be significantly changed by rail transportation. The railroad provided the means of economic transportation of heavy construction materials to many locations previously isolated from the only other form of efficient heavy commodity transport - water.

The railroad also impacted many of the processes and organizational characteristics of the building industry. Parts, supplies or materials could be special ordered from remote plants, warehouses, or production sites. Components such as doors and windows could be prefabricated at a central location and economically transported great distances.

3.7.3   More Railroad Impacts - Measures of Transportation Performance

Three measures of transportation performance are scope (amount of infrastructure), cost, and level of service (speed, capacity). Access to coal and heavy building materials was improved by the railroad in scope (remote coal fields were made accessible), in cost (rail was less costly than wagon transport), and in level of service (speeds were higher than water transportation, and capacities were greater than that of draft animals).

Rail transportation facilitated reorganization of labor enabling productivity improvements. As mentioned, many items could be manufactured at central locations then

sent in completed form to consumers. Transportation costs were small compared to the benefits of both scale and agglomeration economies. Many more producers were made available to the consumer, and markets were enlarged for producers.

Railroads enabled the use of non-local materials and non-local labor through prefabrication of housing components. Standardization of building materials and components began to characterize the building industry. New methods of building were enabled by a transportation system that could move materials precut to standard dimensions. Labor could be trained to work more efficiently with standard materials. On-site labor costs were reduced, as labor reorganized in factories at central locations.

3.8   Housing and the Auto-Highway

3.8.1   The Automobile and Housing Demand

The latest transportation improvement to impact housing production has been the auto-highway system. The automobile allowed cities to expand into the areas between trolley, street car, or other commuter rail lines. The auto also increased available land for those cities without transit systems by increasing the range (radius) of commuting.

3.8.2   The Automobile and Housing Supply

The introduction of the automobile enabled specialization of labor in the housing industry. More efficient commuting to broader geographical areas opened a broader market in which to specialize. Subcontracting of specialized construction components such as plumbing, painting, finish carpentry, and electrical work became commonplace. In addition to commuting, a worker or foreman could now travel to several job sites in a single day. Previously, all work was completed on a house before going to the next. Delays on the part of one work segment slowed the entire process. With the automobile, workers facing delays at one work site could simply move to another house.

The automobile and small truck allowed workers to carry more tools and equipment to the job. Portable equipment such as concrete mixers, generators, and heaters could be moved in or towed behind the worker's vehicle to the construction site, or easily be moved between sites. The use of these tools increased productivity.

Trucks have enabled important changes in the supply of housing materials, allowing the substitution of non-local for local materials at nearly any location.

3.9 Long-term Trends in Materials Supply

It would be interesting to examine the long term trend in distance of building materials transport. However, historical data are not readily available.

Although there are early examples of long distance heavy construction materials transportation before the eighteenth century (Stonehenge, the Great Pyramids), most building materials (stone, clay, and plant products) were obtained within a few miles of the construction site. The introduction of rail and inland water transportation allowed movement of materials over hundreds of miles, but construction utilizing non-local materials was still restricted to the proximity of rail and port facilities.

With the introduction of the motor truck, non-local building materials could be used practically everywhere. The Commodity Transportation Survey conducted by the Bureau of the Census reported that the median distance shipped for most building materials varied from 65 miles for ready mix concrete to over 1000 miles for millwork in 1972. (See Williams [1976b] for means of transport and average transport distances for selected building materials.)

3.10 Trends in Housing Innovation - Prefabricated Construction

Prefabrication is one concept with the potential to reduce housing costs. A review and discussion of this potential and transportation relations is presented in the following sections.

3.10.1 History of Prefabrication

In 1624, the English sent a prefabricated wooden paneled house to America. During the Gold Rush, over 5000 log cabins were built in New York and shipped around Cape Horn to California. During the Civil War the Union Army used standard panels and parts (Arnold and White, 1960). The Eiffel Tower and Statue of Liberty are manufactured structures. However, with the exception of Union Army housing, these represented conventional construction followed by transportation.

Prefabrication as it is discussed in the context of this chapter refers to pre-building for purposes of scale economies and efficiencies. For decades, many ideas and designs for prefabricated housing have been proposed. These designs and procedures have exhibited great potential, but changes within the building industry is slow to evolve. Although many

of the early concepts of prefabrication have been incorporated into a majority of homes (e.g. roof trusses, door frames, cabinets, etc.), prefabrication of complete or nearly complete houses (with the exception of manufactured housing - mobile homes) has not materialized on an economical scale.

The first firm to use prefabrication as we are discussing it may have been the E.F. Hodgson company (founded in 1892). Misawa Homes of Japan was conducting prefab research as early as 1906. Around 1930, Albert Farwell Bemis founded the Bemis Research Foundation of New York. In 1933, this foundation published a report praising the potential of prefabricated wall units and a cubical modular design system. This system allowed the buyer to build their own design with standard pre-made parts. At about the same time, F. Vaux Wilson, owner of the Homesote Company was building wall panels.

In 1934, the U.S. Forest Products Laboratory was formed. This lab tested stressed skin plywood panels and interlocking panels, while the Housing Research Foundation at Purdue University developed prefabricated panel houses. In 1937, the Forest Products Lab built experimental prefabricated houses with the intent of "doing the intricate, difficult part of the work in the factory and thus reducing to a minimum the time and expense of construction on the building site." (Arnold and White, 1960)

In 1936, General Houses first introduced prefabrication on a national scale. Robert L. Davison developed standards for prefabricated materials in the 1930's and 1940's. Other key figures in the development of prefabrication in housing were Howard Fisher, Robert McLaughlin, George Keck, Foster Gunnison, and Ivan Ford, who worked on prefabricated farm buildings (Mason, 1982).

The Alladin Company was an innovator of mobile homes. They designed Pullman type units prior to World War II (Mason, 1982).

The War brought about the magnitude of demand required to economically build prefabricated housing. In 1941, the Tennessee Valley Authority, TVA, built sectional houses - rooms which were built in factories and joined at the site. During the war, over 200,000 prefabricated housing units were constructed (Mason, 1982).

Also in the 1940's, Clayton Powell developed a "semi-prefab" system - a 14 day house. Included in this design were prefabricated windows, doors, and fireplaces which reduced on-site labor requirements (Mason, 1982).

In 1946, the U.S. embarked on an ambitious plan to produce 2.7 million units for the housing shortage by the end of 1947. The plan, the Veteran's Emergency Housing Program, however, failed to produce the desired number of units as precedence was given to peacetime priorities other than housing (Mathieu, 1987).

In 1950 in the United States, one home in ten was prefabricated. By 1960, this figure had risen to one in nine (Arnold and White, 1960). Today, about one-fourth of all single-family housing units are entirely prefabricated (includes manufactured housing). In 1983, 45 percent were constructed with some degree of panelized, modular or manufactured technology. Most homes in the U.S. are still being built on the foundation, with increasing use of prefabricated parts such as trusses and door frames. Although the prefabrication sector leads the building industry in its use of computers and just-in-time inventory control, the industry in the U.S. lags behind that of some other industrialized nations (Japan, Sweden).

3.10.2 Operation Breakthrough

In the late 1960's, the United States Department of Housing and Urban Development (HUD) undertook a program to develop and demonstrate methods of industrialized housing. The primary objective of Operation Breakthrough was to foster research and development in industrialized housing and to show by large scale demonstration that builders could economically produce prefabricated housing. A stated goal of the program was to create housing markets large enough to support prefabrication efficiencies.

The $72 million program did not lead to major changes and was considered by many in the industry to be a failure. However, it did lead to builder exposure to new methods and materials, exploration of new housing construction methods, the encouragement of some building code changes, some support for state-wide building codes, and testing of new labor agreements for industrialized housing (USGAO, 1976).

Several reasons given for the "failure" of Operation Breakthrough were: 1) an unexpected decrease in housing demand during the early 1970's, 2) suspension of mortgage programs by President Nixon, and 3) lack of cost savings potential in some of the developed housing systems. In addition, it was alleged that the program failed to document

cost savings to be gained; however, the time frame for the program was considered by many to be too short (USGAO, 1976). Transportation issues received little attention.

3.10.3   Prefabrication in Foreign Housing Industries

Several other countries have industrialized housing industries more advanced than in the United States. The following sections present a brief introduction to the prefabricated housing industries of Japan and Sweden. In contrast to the dispersed U.S. industry, these two countries have centralized policy making and housing research.

3.10.3.1   Industrialized Building in Japan

Japan leads the United States in introduction of new technologies to industrialized housing. In the Japanese industry, computers, robots, and environmental test chambers are the rule.

Japanese prefabricated housing manufacturers make extensive use of computer aided design (CAD) and computer aided manufacturing (CAM). It is possible for a buyer to sit down in front of a computer terminal with one of the manufacturer's technicians and design an almost custom home made up of combinations of prefabricated sections. Many variations are possible, and when a design is entered, the exact price of the final product can be computed (Dowall, 1986).

The Japanese prefab industry is supported by additional factors. Steel prefabrication is viable due to high population density, demanding building standards due to earthquake and fire requirements, and a moderate climate.

The Japanese government has taken a strong organizational position in the industry. In the post-war 1940's, there was an acute housing shortage, as many homes had been destroyed and few were built during the war. MITI, a think-tank institution, supported the fledgling building (particularly the prefab) industry and the Ministry of Construction (MOC) became involved in all aspects of construction. Organizations subordinate to the MOC include: the Housing Loan Corporation, 1950; the Japan Housing Corporation, 1955; and the Housing and Urban Development Corporation, 1981. The MOC develops 5 year plans which include housing objectives. A boon to the Japanese prefab industry was the adoption of a national building code in 1950 (Building Standards Law).

Important productivity gains have been accomplished by the Japanese construction industry in the past two decades. In a country with only half the population of the U.S. and less land area than California (much of that unsuitable for construction), the industry employs 5.4 million workers in 514,000 firms. Between 1976 and 1986, Japan produced an average of 1.3 million housing units annually. By comparison, the U.S. produced about 2 million units annually (Mathieu, 1987).

The U.S. and Japanese industries differ in level of research. Japanese prefabrication firms each devote 2 to 44 million dollars per year on housing research (compare with the $72 million Operation Breakthrough, the United State's largest research push) [Dowall, 1986]. In the U.S., research and development is not undertaken by construction firms as costs can not be recovered (the benefits will be shared by competitors) [U.S. President, 1980].

A major force in the Japanese prefab industry has been Misawa Homes, which founded Misawa Research in 1906. Misawa's research arm is as large as the rest of the company, and maintains facilities such as an environmental test chamber capable of subjecting an entire house to any atmospheric extreme (Kimura, 1985). An award winning Misawa design consisted of building complete rooms in a factory and erecting them on-site. The Misawa home, however, did not look like a prefabricated house.

In the United States, prefabricated and conventional housing are produced with essentially similar technologies (e.g. components, materials). In Japan, steel framing and ceramics characterize prefabricated housing. Claims of material and transportation cost reductions for some components on the order of a factor of 40 and of labor reductions by a factor of 20 have been made. Average transportation costs for a single family home have been reduced from 120,000 truck/kilometers to 3300 truck/kilometers by use of prefabrication and new materials (Kimura, 1985).

With technical progress, contractors are losing market share to manufacturers. Innovations have reduced costs and the share for prefab has steadily increased (from 9 percent in 1978 to 13 percent in 1983).

Unlike their Japanese counterparts, prefab builders in the United States are not vertically integrated. Due to differences in the skills and expertise required, there are different firms collaborating to produce, market, and erect prefabricated housing.

3.10.3.2   Industrialized Building in Sweden

Prefabrication in Sweden can be traced back to the 18th century with the building of pre-framed wall sections (Mathieu, 1987).

Of the world's building economies, Sweden is unique in that 90 percent of all homes built are prefabricated. However, the prefab industry is comparable in size to that in the U.S. and Japan due to Sweden's smaller housing demand (Sweden's population is about 8 million).

The Swedish government is involved in the housing industry in finance, research, and design of building codes. Two hundred million dollars per year has been dedicated to housing research and development. Loans with 40 to 50 year payback periods are available. There is also a national, performance based building code (Mathieu, 1987). In Sweden, where weather is a critical element in housing, a panel house is typically closed by four men in one working day.

Seventy-six percent of the prefab industry is panel construction, and CAD/CAM is used more extensively than in Japan. The industry is also vertically integrated. The other 24 percent of prefab is composed of modular housing. The average time from order to occupancy of a modular home is merely two weeks.   Some prefabricated houses are exported, a portion being shipped to Japan via the Siberian Railroad. Most units are designed to fit standard 40 ft. containers (Mathieu, 1987).

Sweden employs a slightly smaller percentage (6.8 percent) of workers in construction than in Japan but only a very small work force in residential construction (6800 of 290,000 construction workers are employed in residential construction) [Mathieu, 1987].

3.10.4   Prefabrication and New Materials

With wooden prefabrication, total labor inputs to housing construction in Japan decreased from 417 to 125 person-days per house. Today, with advanced ceramics and prefabrication methods, the labor input for some construction has been further reduced to 21 person-days. Ceramics costing 50,000 yen replace 2 million yen worth of lumber (Kimura, 1985). Although labor rates are approaching U.S. wages, automation has increased productivity and led to cost reductions.

In one Japanese firm, a panelized housing factory employing 85 workers produces a home every 24 minutes. The home must then be erected on site, and labor is required in the production of the raw materials used by the factory. However, this rate of production is equivalent to 4.25 person-days per prefabricated house (Dowall, 1986).

In Sweden, an average 150 m^2 house requires 50 labor hours in the factory, 40 labor hours to erect, and an additional 200 to 250 hours to finish for a total of 290 to 340 hours labor input. This input amounts to 36 to 42 person-days of labor for the finished house, not including labor generated in processing, manufacturing (inputs to the prefab plant), and transportation, trade, and service industries (Mathieu, 1987).

Materials represent a much larger share of the cost for prefabricated construction than for conventional housing. In the production of manufactured housing in the U.S., notwithstanding cheaper unit costs due to bulk material handling, materials account for 65 to 70 percent of the cost (Dowall, 1986). This larger component is of course, share, and the increase is due to reduction in the labor cost component.

3.10.5   Acceptance of Prefabrication

A longstanding constraint to the widespread acceptance of prefabricated housing is aesthetics; many prefabricated structures had institutional appearances similar to factories, warehouses, or truck trailers. While engineers may be quick to point out gains in structural integrity and construction efficiencies, or economists focus on increased economies of production of prefabrication, designers and architects are more conscious of appearance and style. During most of the 20th century, architects have debated the merits of the simplicity of style afforded by prefabricated materials and the familiarity of traditional materials constructed with conventional processes. During the 1960's, prefabricated parts such as concrete or wooden panel sections were covered with facades of traditional materials to produce buildings of more identifiable style (Burnett, 1986). While increasing the cost of prefabricated buildings, the masking procedures were necessitated by market demands.

However, with the introduction of computer aided design, the Japanese have been able to produce some manufactured housing that looks quite similar to something produced by traditional methods. In addition, changing markets and attitudes may be shifting away

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from aesthetics and more toward practicality (particularly exhibited by the needs of the growing elderly segment of the population).

3.11   Present Status of Residential Construction

Today, those trades which utilize higher value materials that are relatively efficiently transported as finished products (window and door framing, truss building, heating/air conditioning equipment, fixtures, and cabinetwork) have been relocated from the job site to the factory. Those trades using materials with high transportation costs (brick work, concrete work) remain on-site for the most part.

Presently, housing labor may be organized into construction and non-construction sectors. Construction labor includes on-site labor (including managing, specializing, and non-specializing labor) and off-site labor (including managing, specialized manufacturing, and non-specialized manufacturing workers).   Non-construction labor includes raw materials producing, materials manufacturing, component manufacturing, transportation and trade, and marketing labor.

Today, on-site residential construction labor is comprised of at least 60 trades. On-site laborers (skilled craftsmen) have to a large extent been replaced by installers. Plasterers have been replaced by drywall installers who apply gypsum board, plywood, fiber-and-pulp boards, and asbestos-cement boards to the interior walls of buildings. All of these boards are fabricated off-site. Truck and rail transportation have enabled the use of such materials.

Those skilled workmen which remain on-site bear a strong resemblance to their predecessors with the exception of their use of new tools. One such tool improving carpenter productivity is the nail gun. On-site laborers, however, suffer from rapidly changing economic conditions and building requirements. Workmen are laid off or rehired as the job progresses, and although better paid (on an hourly basis) than their factory counterparts, have little or no job security or benefits other than those secured or provided by unions.

Prefabrication of bath and kitchen modules has relocated much finish carpentry and plumbing labor to plants. Transportation system improvements have enabled the relocation of labor to the factories which produce these prefab units.

Until the introduction of the truck, prefabrication was generally confined to the production of lightweight components such as windows and doors. Since the early 1900's, the truck has allowed the transportation of heavier, more complete units.

The non-construction segment of housing production includes the manufacture of many ready-to-install components such as pre-hung doors and windows, kitchen and bathroom fixtures, roof trusses, and cabinetwork. A transportation system which is somewhat efficient at moving items of relatively high value and low volume/weight has enabled the widespread application of these pre-manufactured components.

Today, there are two types of builders, speculative builders and owner-builders.

Speculative builders obtain temporary financing and construct buildings to be sold during or after completion. Because the builder is paying for the high-priced short-term financing, speed of construction is of paramount importance. Speculative builders generally try to keep cost down by hiring non-union labor and by expediting construction.

Owner-builders build under the supervision of the owner, who may weigh in quality of construction more highly. Owner-builders are more likely to hire union labor. In either case, time of construction is critical as someone is paying for interim financing or loss of use. It is critical that the transportation system is able to provide labor and materials efficiently and on-time.

The jobs of on-site laborers often depend day-to-day on the delivery of materials or on the arrival of other workers. Carpenters are laid off unless there are adequate materials to continue the job at hand. Due to the cyclical economic nature of the building industry, and to the effects of seasonality, on-site construction labor experiences constant turnover. Industrialization has helped to overcome some of this fluctuation, but tradesmen such as carpenters still may find themselves in and out of jobs with little notice. Due to this variability, it is essential for the worker to have the ability to either change his location or be able to commute to a variety of job sites. The introduction of the automobile provided this flexibility. The automobile also increased the efficiency of building by reducing worker idle time.

3.11.1 Status of Industrialized Building in the United States

While there are an abundance of available data for the prefabricated housing industry, not all references present consistent production figures. This, in part may be attributable to the various definitions of prefabrication. Current estimates for market share of the various sectors are given in the following discussion of the basic types of builders involved in the prefabricated or industrialized housing industry (Mathieu, 1986).

Modular home manufacturers produce five percent of housing units. The original modular principle was to construct all sections in multiples of four feet, thereby accommodating standard sizes of containers, building materials such as plywood, etc. Modular homes are based on components, rooms or modules, which are constructed at a factory, transported on a truck bed, lifted by crane, and assembled on site. Construction quality is relatively high, but so is price unless scale economies can be achieved. In 1985, average costs of construction were $32,000 per module excluding land and market costs. Modules are typically 12 to 14 feet wide and up to 60 feet in length. The modules usually take one to two weeks to manufacture, and the home may be built in one to two months (Mathieu, 1987).

During the Operation Breakthrough program in the United States, prefabricated modules (sections) were transported by rail at $0.55 (1972 dollars) per module mile. At this rate, a typical house constructed of 2 modules could be shipped 1000 miles for $1100.00. By comparison, truck transport of modular or panelized prefabricated units cost approximately $0.75-$1.50 (1974 dollars) [USHUD, 1974].

Panelized construction accounts for 23 to 29 percent of housing units. Panels for interior and exterior walls, roofs, ceilings, and floors including utilities and fixtures are fabricated in the factory. The panels are then sent to the site by truck; except for costs, transportation is usually not a constraint. Although the owner can assemble the panels, quality control is often a problem because of the amount of work that remains to be done on-site.

Manufactured housing (mobile homes) accounts for 12 to 22 percent of housing units. These factory produced homes are the only type of residential construction regulated by a national building code (Manufactured Home Construction and Safety Standards Act of 1974, or HUD Code). These homes are built on trailer foundations. They may be single or multiple unit. Multiple units such as double-wides are transported in single units and

joined at the site. Site work is limited to the joining of the units, hookup of utilities, and optionally attaching the home to a permanent foundation or slab. In 1985, for the 284,000 units shipped, the average size for manufactured homes was 1060 square feet. The average cost was $21,800.

3.11.2   Status of Conventional Housing in the U.S.

Today, site-built homes account for 51 to 74 percent of housing units. Exact figures are not attainable due to inconsistencies in definitions of housing types and because all housing contains at least some prefabricated components.   Builder-dealers produce site-built, manufactured, or prefabricated homes. They produce and sell their product. Production builders (industrialized) are typically large developers who purchase large tracts of land to be subdivided. Work crews are specialized and move from house to house building stages such as foundations, framing, plumbing, electrical, finishing, or other. Scale economies are achieved through the purchase of volume materials. Because all the homes are located in one area, transportation time and costs are reduced.

Component manufacturers prefabricate components that are used in virtually all housing units, depending on the definition of prefabricated component. They range from pre-hung windows or doors to bathroom fixtures to pre-cut framing and finishing components. Some large builders produce their own prefabricated components, and these statistics are not shown in available data. Pre-cut houses may be ordered complete with assembly instructions.

In 1983, 45 percent of all homes constructed in the United States were to some degree panelized, modularized, or manufactured. The remaining 55 percent were entirely site-built (Dowall, 1986).

3.12   The Housing Product

Housing inputs have changed over time. Machine work has been substituted for labor. The jobs associated with building have changed location and composition. New materials have been located, transported, and developed. Building supply and processes of construction have changed. Together with these technological changes, shifts in consumers' demand and disposable income have changed the requirements for inputs. For example, in 1964, the average new home in the U.S. (1240 square feet), required 15 weeks

to build, and cost $14,600 (1964 dollars). By 1969, the average house (over 1600 square feet) required 21 weeks to build, and cost $22,000 (1964 dollars) [Ball and Ludwig, 1971; Roth, 1964].

The Appendix to this chapter contains summaries of several Bureau of Labor Statistics Reports which detail the inputs for various types of housing construction.

3.13   Needs

Migration of population from rural to urban areas, and the limited space of the latter, resulted in a housing supply imbalance. Traditionally, there has been an adequate number of houses on a nationally aggregated level. However, regional shortages have occurred because housing built in rural areas was vacated faster than its salvage rate, while in urban centers, people were immigrating faster than housing was being constructed. Census data show that the current housing shortage is not due to there being more families in the U.S. than there are homes, rather, that available vacant homes are in the wrong location

Today, there is a great need for affordable new housing. The current status of residential construction in America is not able to keep up with demand for this affordable housing. Previously in this study we have discussed the benefits of increased productivity to reducing costs. In subsequent chapters of this report, we will examine the role of transportation in these productivity changes.

3.14 Appendix - Statistical Studies

The U.S. Department of Labor's Bureau of Labor Statistics (BLS) has a program of ongoing studies undertaken to identify the materials and labor requirements for various types of construction, including residential building. An objective of this program has been to analyze the levels and trends of productivity in the construction industry. A direct output of the studies has been single factor productivity analysis of both labor and materials inputs. Although building materials and labor inputs vary geographically, average inputs were tabulated.

Materials used in single-family housing construction, from 1962 and 1969 studies, classified by major categories were: 40 percent lumber and lumber products, 23 percent stone, clay and glass products, 11 percent metal products (except plumbing and HVAC),

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and 6 percent other. The materials were further classified by sub-category and item (Williams, 1972). Higher materials costs in the North Central and Western United States were attributed to higher transportation costs (USDOL, 1964). The ratio of materials to on-site labor costs remained at about two to one for both the 1962 and 1969 studies (Williams, 1972).

The United Nations Industrial Development Organization (UNIDO) has estimated the input of transportation and trade to the construction sector to be about 12 percent in North America (UNIDO, 1984/85). At least one source has attributed 30 percent of the cost of housing production in Japan to transportation (Kimura, 1985).

The transportation component of the construction inputs is not isolated in the BLS reports. To make some account for quality of product, the results reported in this section have been normalized (where possible) for size rather than cost of project. Table 3-1 summarizes the BLS results.

Measures of indirect employment have been calculated with input-output (I/O) tables.

3.14.1 BLS Study: Private Single-Family Housing

In 1962, each 100 square feet of private single-family housing construction required 238 person-hours of labor, 85 of which were on-site. On-site labor represented 22.1 percent of cost, while materials made up an additional 48.2 percent. The remaining 30 percent of costs were attributed to overhead and profit (Ball, 1981). Land and public utilities costs were not included, but selling costs were. The BLS further broke down the 153 off-site person-hours to be 14 hours off-site construction, 72 hours manufacturing, 36 hours transportation, trade, and services, and 31 hours for mining and other (Ball and Ludwig, 1971).

In 1969, each 100 square feet of private single-family housing construction required 218 person-hours of labor, 82 of which were on-site. On-site labor represented 20.4 percent of cost, while materials made up an additional 44.3 percent. The remaining 35 percent of costs were attributed to overhead and profit (Ball, 1981). The BLS further broke down the 136 off-site person-hours to be 16 hours off-site construction, 65 hours

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manufacturing, 32 hours transportation, trade, and services, and 22 hours for mining and other (Ball and Ludwig, 1971).

For each one-thousand 1980 dollars, private single-family housing generated 41.9 hours of total economy employment. The breakdown by industry is: 14.9 hrs. on-site construction, 2.4 hrs. off-site construction, 12.8 hrs. manufacturing, 9.2 hrs. trade, transportation and service, and 4.2 hrs. for other (Ball, 1981).

The Report of the President's Commission on Housing (1982) gave the following cost breakdown for new single-family homes: In 1970, on-site labor accounted for 26 percent, materials for 50 percent, and overhead and profit for the remaining 24 percent of costs excluding land and financing. The report listed the 1980 breakdown as 25 percent labor, 53 percent materials, and 22 percent overhead/profit (Dowall, 1986).

By comparison, wooden prefabricated housing in Japan requires a smaller labor input (15 percent) [Mathieu, 1987].

The BLS has recorded a trend in the ratio of total employment to on-site employment for the construction industry. That ratio increased from 1.11 in 1955 to 1.25 in 1975 (Kane, 1978).

3.14.2 BLS Study: Private Multi-family Housing

In 1971, each $1000 of private multi-family housing construction generated 137.5 person-hours of employment, 50 of which were on-site. On-site labor represented 27.9 percent of cost, while materials made up an additional 47.2 percent. The remaining 25 percent of costs were attributed to overhead and profit (Ball, 1981). Land and public utilities costs were not included. The BLS further broke down the 87.5 off-site person-hours to be 6.5 hours off-site construction, 46.9 hours manufacturing, 26.1 hours transportation, trade, and services, and 8.1 hours for other (Ball, 1981). (Data not available for hours per square foot.)

For each one-thousand 1980 dollars, private multi-family housing generated 48.5 hours of total economy employment. The breakdown by industry is: 17.9 hrs. on-site construction, 2.3 hrs. off-site construction, 15.8 hrs. manufacturing, 9.4 hrs. trade, transportation and service, and 3.1 hrs. for other (Ball, 1981).

3.14.3 BLS Study: Public Housing

In 1960, each 100 square feet of public housing construction required 252 person-hours of labor, 122 of which were on-site. On-site labor requirements on different projects ranged from 68 to 205 hours. Reinforced concrete structures had the lowest average requirement (100 hrs) compared to wood (134) and masonry (147). There was a geographical variation of unskilled labor utilization from north (25-28 percent) to south (45 percent) (USDOL, 1964). On-site labor represented 35.5 percent of cost, while materials made up an additional 47.5 percent. The remaining 17 percent of costs were attributed to overhead and profit (Ball, 1981). Land and public utilities costs were not included. The BLS further broke down the 130 off-site person-hours to be 13 hours off-site construction, 68 hours manufacturing, 38 hours transportation, trade, and services, and 11 hours for other (USDOL, 1964).

In 1968, each 100 square feet of public housing construction required 269 person-hours of labor, 122 of which were on-site. On-site labor represented 32.4 percent of cost, while materials made up an additional 43.4 percent. The remaining 24 percent of costs were attributed to overhead and profit (Ball, 1981). Land and public utilities costs were again not included. The BLS further broke down the 147 off-site person-hours to be 21 hours off-site construction, 70 hours manufacturing, 38 hours transportation, trade, and services, and 18 hours for other (Prier, 1980).

By 1975, public housing construction on-site labor represented 32.7 percent of cost, while materials had increased to 53.1 percent. The remaining 14 percent of costs were attributed to overhead and profit (Ball, 1981). (Data not available for hours.)

For each one-thousand 1980 dollars, public housing generates 49.2 hours of total economy employment. The breakdown by industry is: 22.0 hrs. on-site construction, 4.8 hrs. off-site construction, 12.1 hrs. manufacturing, 7.8 hrs. trade, transportation and service, and 2.5 hrs. for other (Ball, 1981).

3.14.4 BLS Study: College Housing

In 1961, each $1000 of college housing construction generated 236.3 person-hours of employment, 93.6 of which were on-site. On-site labor represented 29.3 percent of cost, while materials made up an additional 54.2 percent. The remaining 17 percent of costs were attributed to overhead and profit (Ball, 1981). Land and public utilities costs

were not included. The BLS further broke down the 142.7 off-site person-hours to be 14.1 hours off-site construction, 77.5 hours manufacturing, 37.2 hours transportation, trade, and services, and 13.8 hours for other (Ball, 1981). (Data not available for hours per square foot.)

In 1972, college housing construction on-site labor represented 36.0 percent of cost, while materials made up an additional 51.1 percent. The remaining 13 percent of costs were attributed to overhead and profit (Ball, 1981). (Data not available for hours).

For each one-thousand 1980 dollars, college housing generates 42.9 hours of total economy employment. The breakdown by industry is: 17.0 hrs. on-site construction, 2.9 hrs. off-site construction, 13.2 hrs. manufacturing, 7.2 hrs. trade, transportation and service, and 2.6 hrs. for other (Ball, 1981).

Other studies of building material and labor requirements conducted by the BLS included commercial office buildings, elementary and secondary schools, federal-aid highways, federal office buildings, civil works, sewers, general hospitals and nursing homes. Because of the important organizational and supply differences between the housing and heavy construction industries, the results of those reports were not considered directly applicable to this study.

Table 3-1: Construction Cost Breakdown

	On-site Labor	Materials & Equip.	Profit & Overhead
Private	22%	48%	30%
Single-Family Housing	20%	44%	35%
Japan Wooden Prefab	15%	?	?
Private Multi-Family Housing	28%	47%	25%
Public Housing	36%	48%	17%
	32%	43%	24%

	33%	53%	14%
College	29%	54%	17%
Housing	36%	51%	13%

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4   Innovation in the Housing Industry

4.1 Introduction

As has been stated, transportation development relates to production in two ways: (1) it may improve the performance of given activities, or (2) it may create opportunities for new activities - products, services, institutions, etc. In the latter case, the proximate cause of improvements is innovation, and innovations may be involved in the former case as well.

> "Innovation is of importance not only for increasing the wealth of nations in the
> narrow sense of increased prosperity, but also in the more fundamental sense of
> enabling men to do things which have never been done before at all." (Taylor,
> 1987)

Jacob Schmookler (1972) has suggested that the technological capacity of an economy can be defined as the accumulated body of technical knowledge weighted by the number of persons who have access to this knowledge. The number of persons with access to knowledge is facilitated through transportation as this knowledge is embodied in goods and services delivered or provided by transportation. This briefly noted concept will be used in a later treatment of the diffusion of wallboard technology.

Another concept of potential use is the theory of economic long waves The section to follow examines the forms of innovations according to when they occur during the three phases of the life cycle of a product or system: introduction, rapid deployment, and maturity. Next, a list of important housing innovations is identified. Examination of this list leads to two additional classification levels which are presented in the in the next two sections: impact of innovation (e.g. on labor, cost, quality of housing) and arrangement of causality (between transportation improvements and housing innovations). In order to provide a framework for the analysis of the relations between transportation and housing productivity, and for the examination of related policy issues in a systematic manner, a typology for classification of housing innovations is presented whose dimensions correspond to the classification schemes described above. Innovations can be classified according to this typology. This classification facilitates systematic analysis of innovations with like characteristics.

4.2 The Long Wave Concept

First articulated by the Dutch Marxist van Gelderen in 1913, the concept of long cycles in market economies is not novel (Freeman, 1982). The Russian statistician Nicolai Kondratieff elaborated on and propagated the study of the existence of such cycles in a series of papers which included a basic essay called "Long Economic Cycles." The essay was published in *Voprosy Konyunktury* (Problems of Economic Conditions) in 1925 (Kondratieff, 1984). These cycles, with 40 to 60 year periods, are often referred to as Kondratieff Cycles or long waves.

Joseph A. Schumpeter, the late Harvard economist identified three long waves in recent history, the first associated with the industrial revolution, the second tied to improvements in transportation, chiefly the railroad, and a third connected with electric power, the telephone, and the automobile. Building on the theories of Kondratieff and early work by Schumpeter, Simon Kuznets proposed a dating scheme for economic long-waves occurring since the later eighteenth century (Kuznets, 1953). Each cycle consists of periods of prosperity followed by recession, depression, and finally recovery. J. J. van Duijn has updated the work of Kuznets to the mid 1970's (Van Duijn, 1977). Upswings in the economy associated with the three long waves have been dated to the 1790's, 1840's, and 1890's. The period of economic prosperity after World War II has also been related to the long wave.

Alan Graham and Peter Senge have built on the pioneering work in economic long-wave theory by Kondratieff, Schumpeter, and Kuznets. In their paper, "A Long Wave Hypothesis of Innovation," Graham and Senge emphasized expansion of the capital-producing sectors as a primary cause of the long wave (Graham and Senge, 1980). The paper utilized a variety of data on long-term trends in innovation collected by Gerhard Mensch.

In his book, *Stalemate in Technology*, Mensch presented data to support a theory that innovations occur in waves, which is consistent with Schumpeter's hypothesis that innovations and long-waves are related (Mensch, 1975). Mensch classifies innovations into three categories which were useful in the work of Graham and Senge (see the following section for Mensch's classification scheme). We will make use of this classification terminology as we introduce and examine the relations between transportation improvements and productivity changes associated with economic long waves.

4.3 Forms of Innovations

Mensch utilized the product cycle concept to frame his definitions of innovation. Any given product or service begins its "cycle" of production with its invention, which is followed by introduction to the market, first increasingly, then decreasingly rapid deployment or adoption, and finally saturation of the market or particular niche. Mensch describes three types of innovation that occur during the cycle: basic, improvement, and pseudo.

Basic innovations are the introduction of new technological or social products or combinations of products which create new branches of industry, offer new employment opportunities, develop new markets, or attract capital from stagnating branches. Basic innovations enable the first phase of the product cycle, the introduction. Design standards are developed within this regime.

Once the product is introduced and begins to claim a market, price reductions are facilitated by standardization and scale economies.

Improvement innovations occur during the rapid deployment (growth) phase of the product cycle. By enhancing function, safety, durability, and/or lowering the cost, improvement innovations increase demand for products and services. Demand continues to grow beyond initial market saturation as consumers replace first generation goods with new and improved models so long as there are continued real improvements.

In spite of these improvements, the choices made during introduction are locked in as more money is invested in capital (plant, tools, infrastructure, etc.) to produce standardized products at efficient scale.

Finally, Mensch defines "pseudo-innovations." Pseudo-innovations include those improvements designed to increase or retain market share. These innovations support price increases by sales promotion and minor product differentiations such as changes in comfort, color, options, etc.

Pseudo-innovations occur during the late phases of product cycle, where the total market is no longer increasing in size. Producers may turn to exports for increased output, demand is characterized as inelastic, and fewer and larger companies provide a decreasingly competitive supply.

At product or system maturity, capital has been fully depreciated (equipment is out-dated, buildings and infrastructure are approaching design life, maintenance cost exceeds capital cost). Money is freed up for basic research, development and new production facilities. At this stage, labor becomes plentiful as substitution of capital for labor with associated improvements in labor productivity have peaked. The stage is set for a new round of innovation, and markets for new products and services await exploitation.

Using the product cycle construct, Mensch identified when innovations would be likely to occur within the Kondratieff wave. He proposed that during depression inventions have a better chance at becoming innovations. It is at this time, when products of the old cycle are mature (real benefit has been mined out), that opportunity for new products and services is greatest.

Improvement innovations occur as the economy recovers and markets grow. During prosperity, most everyone has access to the products produced during the cycle and improvements are limited to minor or pseudo innovations. Market size is no longer increasing. This slowdown leads to recession; price increases without real improvement cause "stagflation," (Mensch, 1979) and the long wave is complete.

Schumpeter, Mensch, and Graham and Senge have each developed theories that relate innovation to the long wave. Our work differs from these and other innovation theories by focusing on the improvements and developments in transportation as factors underlying the long wave in one branch of industry, housing production.

Cesare Marchetti of the International Institute for Applied Systems Analysis (IIASA) has extended the long wave concept to transportation analysis and has presented some data to show how growth of transportation systems follow S-shaped curves. On a logarithmic scale, the S-shaped curves appear linear, and Marchetti uses this tool to show the growth of canal, rail, and highway infrastructures in the United States (Marchetti, 1985).

Using Mensch's data, Marchetti correlates basic innovations and economic long waves. (Marchetti, 1988)

4.4   Identification of Innovations

With the original intent of reproducing the Mensch/Marchetti approach, we compiled an eclectic list of housing innovations and developments. (Due to length, the list is presented in the Appendix to Chapter 4.)   An examination of this list shows that some innovations are processes, others are products (perhaps not all the innovations on this eclectic list should be considered innovations).   In addition, other classification schemes come to mind.   The following two sections describe two of these schemes: impact of innovation and arrangement of causality.

4.5   Impact of Housing Innovations

Some of the innovations identified in the preceding section involve replacing human or animal power with machine energy (e.g. power tools). Other innovations involve better designs or structural methods. Still others replace on-site labor and methods with off-site labor and capital. Some innovations have important transportation components (access to non-local materials), others do not (the nail gun). Some innovations reduce cost (better use of energy, design, higher labor productivity), while others improve quality (modern electric appliances, insulation).

4.6   Arrangements of Causality

Globally, transportation improvement may lead to a Mensch-like burst of innovation in many sectors. Or, a burst of technological innovations may present obvious transportation applications which, in turn, lead to transportation improvements. An additional scenario might be availability of capital and/or labor leading to general technological innovation encompassing both transportation and non-transportation improvements. Still another

possibility is an innovation burst creating demand for products or services which in turn demand transportation improvements to serve new markets. A variety of examples for each of these as well as other arrangements of causality may be identified in several sectors of the economy.

With respect to housing, we propose that transportation improvements enable bursts of innovations in materials supply and the organization of labor. Classic concepts of what transportation improvements do for production apply. Transportation improvements: 1) increase access to old resources and make new ones available, 2) enable specialization of production and consumption, yielding increased choices for consumers and producers, 3) offer opportunities for economies of scale and scope, and 4) provide for agglomeration economies (interdependent activities can be synchronized at times and places, common resources may be used by different actors). We are adding a fifth: 5) transportation enables Schumpeterian changes in production (facilitates innovation).

Sometimes, general technological innovations generate improvements in both housing production and transportation. Innovations in transportation and housing may occur independently within a wave of technological innovation.

We may also observe a feedback relationship whereby transportation improvements foster productivity enhancing reorganizations which in turn generate new demands on transportation systems.

It is also possible that, due to the size of the housing industry, an important innovation in housing production may produce a demand for transportation improvements or even a new specialized method of transport.

4.7 Typology of Housing Innovations

4.7.1 Typology Motivation

This brings us to the motivation for creating a typology for classification and examination of housing innovations. We are striving to (and later in this thesis we do) make estimates of the social gains associated with transportation development for a particular housing innovation (the substitution of drywall for plaster, see Chapter 6). By extending this analysis to similar innovations, we can make estimates of the gains in productivity enabled by transportation for an entire class of housing innovations. We therefore developed a typology

that can be used to pull out a class of innovations to be given special attention. There are other potential uses for such a typology. For example, the typology's first dimension is "form of innovation." This classification would facilitate innovation burst analysis (correlation of housing innovation frequency with the long wave or with transportation development).

More specifically, for a given housing innovation, we can estimate the difference in social benefits between 1) the innovation given transportation development as it occurred and 2) the innovation given no improvement in transportation. The general concept of analyzing the

Possible Impact of Transportation Improvement
on Adoption or Substitution of Innovations

Figure 4-1
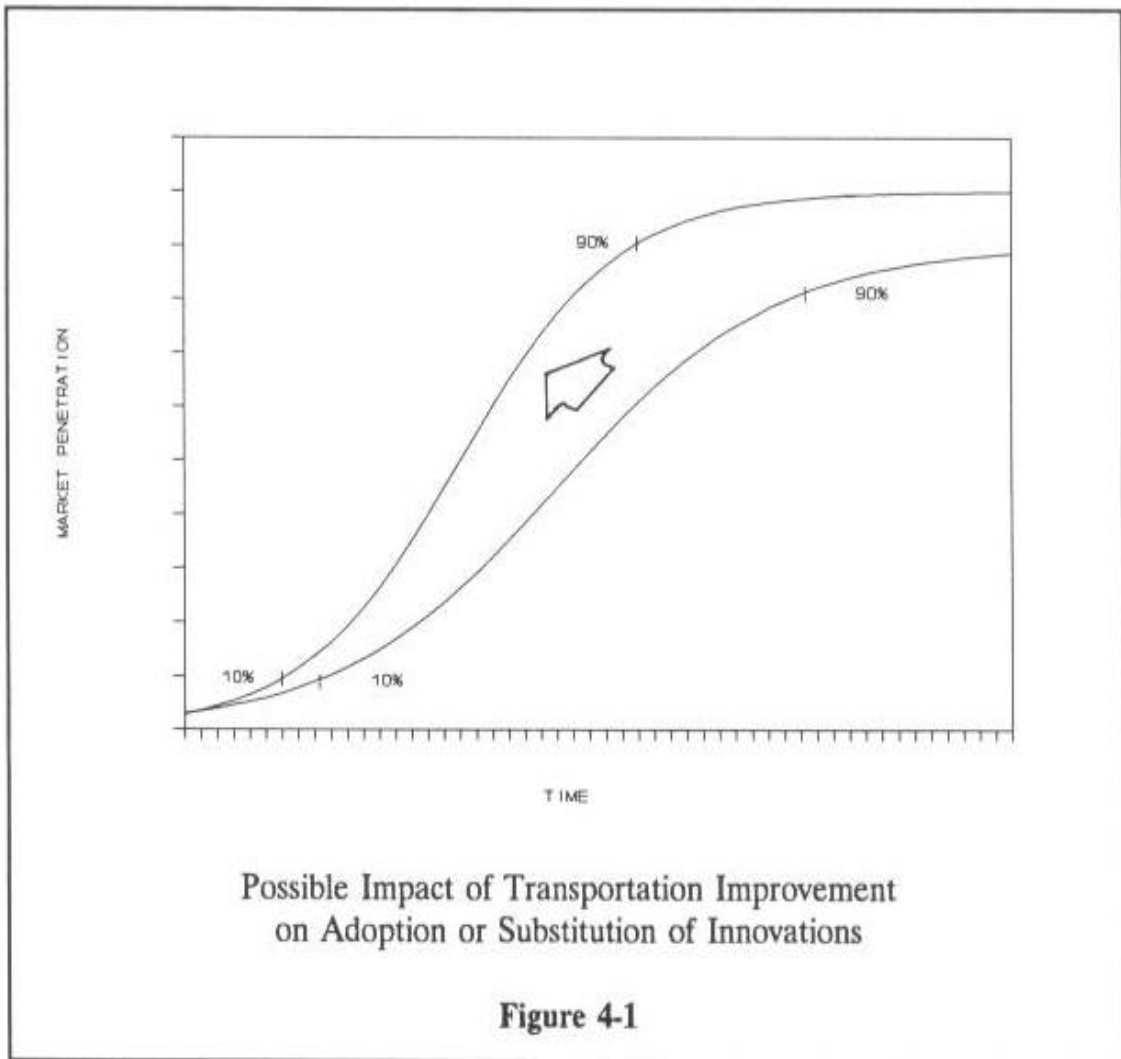
economic impact of transportation system development in this fashion is not new to this study. Robert Fogel estimated the benefits of the U.S. railroad system. Fogel derived social costs by substituting direct transportation costs of existing forms of transportation (water/canal) for

rail costs, and did not account for changes in production technology (Fogel, 1964). In this study, we are interested in the ways in which transportation changes production.

We desire an estimate of the social gains from both reduced direct transportation costs and reductions in production costs due to transportation improvements. We have seen that the adoption of innovation can be shown by S-shaped curves. The impact of transportation on this process can have two important impacts. Improved transportation may 1) change the rate at which innovations are adopted, and 2) change the level of innovation adoption (see Figure 4-1).

For example, drywall construction would have substituted for plaster and lath with or without deployment of the truck-highway system. The question is to what extent and at what rate would the substitution have occurred without the truck? With the truck-highway system, the time from 10 to 90 percent market penetration for wallboard was 43 years (see Chapter 6 for analysis). If this rate was faster than it would have been given only the rail system, or if the saturation value of over 90 percent would have been lower, the truck system offered some social savings beyond direct cost reductions. In Chapter 6 we consider these questions when we compute an estimate for the social gains enabled by the impact of the truck-highway system on the diffusion of the drywall innovation.

4.7.2   Structure of the Typology

For the first dimension of the typology, we employ Mensch's definition of "form of innovations." The three levels to be used for this dimension are: 1) basic innovation, 2) improvement innovation, and 3) pseudo innovation.

The second dimension of the typology is impact of innovation on production. The levels for this dimension are 1) innovations that replace human or animal power with machine energy in both on and off-site construction processes, 2) innovations in structural design or knowledge, 3) innovations that improve production by improving the productivity of the laborer, 4) innovations that replace on-site labor with off-site labor and capital, 5) quality improving innovations, and 6) innovations based on improved access to non-local materials.

The third and final dimension of the typology classifies according to arrangement of causality between transportation and residential construction. Levels are 1) transportation improvements facilitate housing innovation, 2) housing innovations place new demands on

transportation (feedback), 3) an innovation outside transportation and housing causes improvements in each (common causation), 4) housing innovations and transportation improvements are part of a general wave of technological innovations (wave dependent), and 5) independent (housing innovations occur independently of transportation improvements). Table 4-1 shows the dimensions and levels of the typology.

Table 4-1
INNOVATION TYPOLOGY

Dimension I: Form of Innovation

1) basic
2) improvement
3) pseudo

Dimension II: Impact of Innovation on Production

1) replacement of human or animal energy with machine power
2) better structural design or knowledge
3) increased laborer productivity/efficiency
4) replacement of on-site labor with off-site labor and capital
5) improved quality
6) improved access to non-local materials

Dimension III: Arrangements of Causality between Transportation and Housing Innovations

1) transportation improvements lead housing innovations
2) housing innovations place new demands on transportation (feedback)
3) common cause (force outside transportation and housing)
4) general wave of technological innovations
5) independent

4.8 Conclusion

In this chapter, we have discussed the concepts of innovations and long waves. We have identified a list of housing innovations and developed a typology for classification of these innovations.

At this point, we do not apply this typology to the list of innovations. That would be a large, interesting effort, but not one requisite to our work. Rather, after our analysis of the wallboard innovation in Chapter 6, the typology could, for example, be used to identify other innovations in the same class as wallboard. The inferences from the wallboard study could then be generalized to innovations of its type.

4.9 Appendix to Chapter 4 - Housing Innovations

DATE	Innovation
1150-1250	Transition from earth to sill mounted footings
1212	Thatch roofs prohibited in London
c. 1212	Royal ordinance: London reed/rush houses to be covered w/plaster
1238	Slates first used at Woodstock
1200-1300	Wood paneling introduced in England
1200-1300	Lap joints in use
1200-1400	Scarf joints first used
1200-1600	Jettying popular (upper floor overhangs)
1400-1500	Two-story houses become "general"
1450	Decline of Large-framing
1477	Size of tiles defined by statute (Britain)
c. 1590	Wall paneling first introduced to houses
1528	Lath size standards ordered in England
1500-1600	Advent of the truss
c. 1550	Plaster ceilings come into use
1567	Crown glass invented
c. 1590	Oak becomes universal for housing
c. 1600	Modern staircase design
1610	Governors palace at Sante Fe constructed of Adobe
1611	First English timber-framing in the USA
1615	Wood houses built in Jamestown
1615	Brick construction introduced in USA
1610	Introduction of the joiner's mitre
1622	Early heavy timber framing at Plymouth Mass.
1625	First power-driven sawmill - Jamestown
1628	Brick kilns open in New Amsterdam
1628	Brick kilns in operation, New Amsterdam
1633	Power-driven saw mill, Virginia
1637	English law requires brick homes on southern plantations

1638	Swedes introduce the log cabin to America
1638	Swedes introduce log house to USA
1642	Early adobe construction - San Estevan Church, Acoma, New Mexico
1647	Straw roofs banned in New Amsterdam
1600-1700	Rise of scientific structural analysis
1600-1700	Plaster first used to replace clapboards or weatherboards
1650-1700	Bricks cost 8s.-15s. in Virginia, 18+s. in England (per 1000)
1600-1700	Double layer of boards used for flooring
1650	First shingled house, Long Island (Dutch)
1654	First brick house in America (Virginia)
1654	Slate roofs first used in Boston
1675	Thatch used for roofs in England before this time
c. 1690	Bricks first used extensively in the south
c. 1690	Pine replaces oak for flooring
c. 1690	First wall paneling
c. 1680	Rain gutters become common
1681	First truss framing in the US - Old Ship Meeting House, Hingham, Massachusetts
1682	Philadelphia, 1st homes: cave-type dugouts, dirt heaped on timber roofs
1698	S.J. Bentham (England) patents various woodworking machines
c. 1700	Extra layer of sheathing board used for insulation (replace wattle/daub)
1600-1700	Stone houses popular in Hudson Valley
1700	End of most cruck construction
1720	Wooden sash windows become more popular than casement windows
c. 1710	Wall paper becomes popular
1724	Shop-made double-hung windows advertized by John Boyd, PA
1724	Carpenters' Company Established in Philadelphia
1725-1780	Brick becomes the great building material
1725-1800	Finished/polished hardwood flooring replaces pine
1742	Ben Franklin Stove invented
1744	Ben Franklin fireplace
1772	Pine pitch or tar & gravel roof invented
1774	London Building Act encourages use of stucco
1774	London Building Act prohibits use of exposed timber details
1775	Slate roofs become more common in the USA
1775	Exterior paint becomes common in America
1777	Circular saw (Miller - England)
1780	Red clay tile roofs first made in Mission San Antonio, California
1790-1830	Nail and spike cutting machines introduced
1792	Gas lighting (Murdoch - Scotland)
1792	Glass manufacture commercially est. in the USA
1796	First hydraulic cement
1700-1900	Softwood and nails replaces oak for housing
1800-1810	Steam-heating introduced
1808	Band saw (Newberry - England)
1814	Power-driven circular saw introduced to the US
1819	Natural hydraulic cement patented (Canvass White - USA)
c. 1820	Zinc roofing introduced
1824	Portland cement (Aspdin - England)
1824	Portland cement

1825-1850   Interior paint becomes common in America
1829   First manufacture of bricks by machine
1832   Balloon framing invented in Chicago by G.W. Snow or A.G. Taylor
1830-1840   Machine-made nails were available
1836-1837   Intro of the steam excavator (W.S. Otis - USA) 3/8 cost of hand labor
1836   Galvanizing process invented
1840   Howe truss patented
1844   Pratt truss patented
1849   Hollow clay blocks patented by Roberts
c. 1850   Swedish factories prefab log houses and ship to distant construction sites
c. 1850   Molding becomes a trade
c. 1850   Introduction of the planing machine; stock millwork becomes important
1800-1900   Tin plate roofing becomes common
1851   Cylinder lock (Yale - USA)
1850-1860   Reinforced concrete construction invented in France and Great Britain
1857   Wire screening introduced to doors and windows
1857   Concrete mixers introduced (Hungary)
1858   First mechanical stone crusher (USA)
1860   Introduction of linoleum flooring (Walton - USA)
c. 1860   Compressed air power transmission
1860   Prefab house and barn units manufactured in NYC, Boston, Chicago
1865   Thermoplastics invented by Joseph Parkes of Birmingham
1865   Pneumatic tool (Law - England)
1860-1870   Pneumatic drills introduced
1866   Large-scale production of sand-lime bricks begins in England
1866   Practical pneumatic rock drill
1870   Pre-hung door patented
1871   Compressed air rock drill (Ingersoll - USA)
1871   Artificial Portland cement patented (USA)
1871-1876   First reinforced concrete building in the US, Ward House, Port Chester, NY
1872   Factory sash, door frames, moldings, doors, and blinds were avail.
1876   Carpet sweeper (Bissell - USA)
1877   Electric welding (Thompson - USA)
1879   Factory-made built-up fireplace mantels made available
1879   Introduction of electric lighting (Edison - USA)
c. 1880   Hollow clay blocks common for floor construction
1880   Shift from steam to hot water heating
1888   Prestressed concrete invented in the U.S.
1889   13/16 in. adopted as standard thickness for pine flooring
1895   Invention of Gypsum Wallboard (Sackett - USA)
1896   Electric stove (Hadaway - USA)
1901   Electric washer (Fisher - USA)
1904   Eugene Freyssinet conceives the idea of prestressed concrete
1905   Modern prefabrication
1907   Electric vacuum cleaner (Spangler - USA)
1907   Bakelite (Baekeland - Belgium/USA)
c. 1910   Precut lumber gets its start in S. California by several builders
1910   Kitchen cupboards first manufactured by Curtis Companies of Iowa
1911   Air conditioning (Carrier - USA)
1915   Mechanical refrigerator introduced

1916 Bakelite plastic produced
1919 Arc Welder (Thompson - USA)
1925 Introduction of circuit breakers (Hilliard - USA)
1930 Freyssinet technique for prestressed concrete widely applied
1930 Ready-to-install window units
1937 First laminated-timber construction in US, Jamestown, ND - Municiple Auditorium
c. 1938 Eugene Freyssinet makes prestressed concrete economical and practical
1938 First prestressed concrete structure in US, St. Paul Minn., Water-tank
1940-1950 Introduction of particle board
1940-1950 Millwork standardized

OTHER INNOVATIONS (Dating not determined)

foil-faced rigid insulation board
laminated veneer lumber
concrete pump
steel windows
aluminum windows
standard lumber (width and depth)
standard length lumber
precut lumber (stacked for use)
chain saw
powered table saw
powered routers
powered lumbering machinery
powered sanders
powered drills
manufactured folding stairs
manufactured stair balusters and spindles
manufactured stair stringers
prefab room modules
prefab wall panels
manufactured wood moldings (cornice, baseboard)
pre-hung doors
manufactured roof trusses
manufactured windows
manufactured doors
manufactured housing (mobile-homes)
manufactured basins
manufactured bathtubs
flush-toilets
pre-hung windows
manufactured window frames
manufactured door hardware
manufactured window hardware
manufactured door frames
manufactured cabinets
manufactured fireplace units
electric appliances

manufactured waste disposal systems (ceptic tanks)
indoor plumbing
manufactured shelving
gas lighting
gas appliances
manufactured concrete forms (reusable)
manufactured scaffolding
aluminum ladders
automatic lawn sprinkler systems
reinforcing welded wire fabric
polyethylene vapor barrier
fiberglass insulation
portland cement concrete
central heating (with duct work)
ready-mix concrete
plastic laminates (for kitchen and bath surfaces)
metal siding
pre-finished metal siding
sheet metal (for flashing and roofs)
asphalt/felt fiberglass insulating mineral fiberboard
asphaltic or paraffin building paper
plastic (PVC) pipe
asbestos asphalt shingles
acoustical mineral fiberboard and tiles
roofing felt
hollow-core doors
plywood
soft-boards (building boards from waste)
laminated beams
wall-to-wall carpet
split ring connectors
hardboards (building boards from waste - paneling)
particle board from waste laminating glues
floor tiles (asbestos, asphalt)
metal splice connectors
machine-made wire nails
electric junction boxes
nail gun
staple gun
corrugated metal fasteners
portable electric planer
portable electric sander
portable electric router
portable electric drill
portable electric saw
power concrete finishing tools
insulation blowers
portable concrete mixers (powered)
paint sprayers
portable on-site gas or electric heaters

building ceramics
building robotics
CAD/CAM
"smart" houses

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5   Housing and Transportation Trends

Our general objective has been to improve understandings of the relations between transportation and production. On a very basic level transportation enables production by moving people and goods.   More specifically, transportation improvements increase access to materials, consumers and producers. By facilitating scale, scope, agglomeration, and inventory reduction economies, transportation developments decrease the real cost of production.

The present chapter provides trend data on transportation and production (construction), emphasizing housing. Time series data to be presented reflect rapidly maturing transportation systems and reduced productivity in housing construction. The purpose of this chapter is to place remarks made earlier, such as examples of changes in housing technology, in temporal frames, provide time series data on growth and change, and explore simple relationships between housing and transportation trends.

This chapter is organized in three major parts. First, transportation data are presented. In general, these data reflect S-shaped trends in transportation system deployment.[3] The second section provides time series data for the construction industry. Data specifically for housing construction were obtained where possible. However, due to reporting methods and scope of coverage, building data were sometimes more comprehensive than housing data. In the third and last section of this chapter, trend comparisons are presented along with discussion of the extent to which transportation and housing production trends correspond.

In the previous chapter, we examined the relationships between transportation improvements and housing innovation. We discovered that the relationships were not always direct or simple. Similarly, the conclusions to be drawn from the comparisons of transportation and housing trends in this chapter include some supported with (roughly) direct correspondence and others that require interpretations that go beyond direct, simple comparison.

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[3]See chapter 4 "Innovation in the Housing Industry" for a discussion of S-shaped curves, long wave theory, and the product cycle concept.

The life cycle construct provides a useful language for discussion of our thesis that the relations between transportation improvements and housing productivity are strong, and that gains in housing productivity are fostered by transportation system development. We conjecture that in the early stages of transport system life cycle, many new opportunities for innovation in housing are presented - opportunities for more effective labor organization or materials supply. Further, during the late stages of transport deployment (maturity), few opportunities exist for such productivity enhancement. To validate these hypotheses, we will present trend data and analyze them in the life cycle framework.

To characterize stage of transportation development and to facilitate comparison with housing construction trends, a simple logistic growth model is fit to some of the transportation data. The following section describes the method used to estimate the parameters of these equations.

5.1 Curve Fitting

Product life cycles, as mentioned in Chapter 4, can be modeled by S-shaped curves (any equation in which the dependent variable increases slowly at first, then exponentially to a point in time, then increasingly slower to asymptotic growth). Sometimes, the upper limit of growth may not be an asymptote (a system may actually decrease in deployment after a certain time, e.g. railroad mileage). Alternatively, and particularly in transport systems, system maturity is characterized by oscillation around a set point (e.g. saturation of truck share of the freight market).

Several models are available to treat growth processes. These models, which include modified exponential, Gompertz, logistic and others, yield S-shaped curves. A particularly useful S-shaped curve is the three-parameter logistic (also known as Pearl-Reed) function. This function has the property of constant ratios of first differences symmetrically distributed about an inflection point which occurs at half the saturation value.

Fitting the three-parameter logistic growth model to the transportation data required estimation of the three model parameters. The form of the chosen model is:

$$X(t) = \frac{K}{1 + e^{(-\acute{a}t - \hat{a})}} \tag{1}$$

where: X(t) = the value of the dependent variable at time (t),

K = the saturation value for the dependent variable X,

á = a parameter controlling the rate of growth, and

â = a parameter positioning the function in time.

Our first attempt to estimate model parameters consisted of log linearizing the equation (with appropriate data conversion) then applying ordinary least squares (OLS) linear regression.   While OLS produced high correlation coefficients, results were obviously biased (values below an initial value or exceeding the saturation value were not allowed, and non-weighted least squares overcompensates errors for large values of the dependent variable).

Next, following a method presented by Nakicenovic (1988), a nonlinear weighted-least squares regression program (FIT) was written to estimate the logistic model parameters. The program requires specification of a range for each of the three logistic model parameters. Although the physical interpretations for the parameters given above are clear, the values for á and â are not intuitively apparent. To facilitate specification of parameter ranges, a transformation was applied to the parameters.   The resulting transformed parameters have more intuitive interpretations.

Given a range for each parameter (specified by a minimum value, an increment size, and the number of times the parameter should be incremented), the FIT program computes the weighted sum of squared errors for all combinations of the three parameters over each of their ranges. The program records parameter values which minimize the sum of squares. (See Appendix 5 for a description of the weighting technique and the FIT source code listing.)

We followed a parameter transformation presented by Nakicenovic.   A brief summary of this transformation is presented here.

Because the logistic function is symmetrical, the maximum rate of growth occurs at the inflection point, we call it t_{50}, where the value of the function reaches half the saturation value, (X=0.5•K). Substituting into equation (1) and solving for t, we obtain (t_{50}=-â/á). A growth rate, $\ddot{a}_t$, may also be defined as the time required for the function to grow from 10

to 90 percent of the saturation value (t_{90}-t_{10}). Solving equation (1) for t_{90} (t at X=0.9•K) and t_{10} (t at X=0.1•K) yields $\ddot{a}_t$ = (ln81)/$\acute{a}$ = 4.394/$\acute{a}$. In terms of the clearly more intuitive redefined parameters, the original parameters can be derived:

$$\acute{a} = 4.394/\ddot{a}_t \qquad \hat{a} = \frac{4.394 \cdot t_{50}}{\ddot{a}_t}$$

5.2 Transportation Trends

This section presents data assembled to identify stages in transportation system deployment. Because changes in housing production occur in materials supply and labor organization, measures for freight (materials) and passenger (labor) transportation were identified. Because a sector as large as housing construction uses transportation services in many different ways, several groups of data within each of the two broad categories of transport were analyzed. These groups are: 1) vehicle use, 2) vehicle performance, 3) vehicle access, and 4) infrastructure development. The most extensive data were available for the present century, so scope is limited to the auto/truck highway system. However, railroads had an important impact on the organization of housing production. Where appropriate, comments are made on the impact of this system.

5.2.1 Freight

Although approximately 25 percent by weight (less by value) of building materials are transported by rail (Williams, 1976b), the transportation dynamics with the greatest impact on building materials during this century has been deployment of the auto/truck highway system.

We may observe that the rail system grew to its maximum areal extent by about 1925. Using size as a measure, the system had matured. Evidence supporting this observation is readily available, and has been effectively summarized by a Federal Railroad Administration report:

"Sometime during the first two or three decades after 1900, the railroad industry reached its peak in size. It is difficult to say exactly when the peak occurred because no single measure satisfactorily represents the size of the railroad industry. The

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following statistics (see Table 5-1) indicate that it occurred sometime between 1907 and 1930." (USDOT, 1979)

Table 5-2
RAILROAD STATISTICS

Measure	Peak Year	Peak Amount
Number of Operating Railroads	1907	1,564
Miles of Road Owned	1916	254,251
Passengers Carried	1920	1,269,913,000
Employment	1920	2,076,000
Locomotives in service	1924	69,486
Freight Cars in Service	1925	2,414,083
Passenger Cars in Service	1926	65,763
Miles of First Main Track Operated	1929	260,570
Miles of Total Track Operated	1930	429,883

Source: (USDOT, 1979)

Since the peak of railroad deployment, truck transport has captured an increasing freight market share. Therefore, we concentrate on the development of motor trucks, automobiles, and the highway system as the transportation dynamic impacting housing during most of this century.

To show the maturity of the rail system and to demonstrate the application of S-curves to describe system growth, we have used the FIT program to estimate the parameters for a logistic equation modeling U.S. railroad mileage from 1830 to 1930 (see Figure 5-1). Estimation of the saturation value, K, was not necessary, as we know the value to be about 250,000 miles. From the data we could approximate values for $\ddot{a}_t$ (time between 10 and 90 percent saturation) and t_{50} (time at 50 percent saturation). This enabled us to specify a range for these parameters as input to the FIT program which searches for the "best" parameters within the ranges.

Using the model (partly to smooth out fluctuations in raw data), we can say that by 1884 half of the maximum railroad mileage was deployed. After 10 percent of the railroad mileage was built, it took 47 years ($\ddot{a}_t$) for 90 percent of deployment; t_{90} (1908) can be used as an approximate date for system maturity (using mileage as a measure). Although rail ton-miles continued to grow after this date, miles of rail decreased. And as the data presented in the next section will show, motor freight carriers captured share from existing markets for rail freight as well as share of freight for markets appearing after rail system maturity.

5.2.1.1   Use of Trucks

The first data set we present for the auto/truck highway system shows the trend in motor truck freight as a percent of all intercity freight (See Figure 5-2). In this trend, we observe the clearly defined transitions characteristic of logistic system growth (S-curve), from flat to rapid increase (sometime before 1940), and from rapid increase to flat (around 1960). The FIT program was used to fit a curve of simple logistic form. Data for 1942 to 1949 were not used in the regression.[4] Results indicate that trucks had captured 50 percent of their potential market share by 1944 and 90 percent by 1963. Today, motor truck freight share is oscillating around an equilibrium (about 24 percent).

Specifically, we are interested in how freight transport affected the building industry. Cement and building materials transportation are given as examples.

Figure 5-3 shows the trends in motor truck share of the cement freight market. The data are for shipments to ultimate consumer in tons. Although shipments in ton-miles would indicate a higher market share for rail, (average distance shipped by rail is longer) the data show saturation of truck market share after S-shaped growth. Our data do not go back far enough to show the early stages of this trend. However, we speculate that the transition from flat to rapid increase occurred around 1950. Using the FIT program to estimate a logistic model for the market penetration process, we estimated a saturation

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[4]During World War II, due to fuel, oil, rubber, and motor vehicle shortages, some freight, which under peacetime conditions would have been shipped by truck, shifted to the railroad. In addition, the railroads also carried much of the materials and supplies needed for the war effort.

market share of 88 percent, 90 percent of which (79 percent market share) was attained by 1970.

Because trucks are more efficient than railroads for hauling cement in most markets, trucks have captured a large share of that market. The efficiency of trucks over rail provided direct savings in the form of lower costs and increased productivity because cement could be hauled to more places faster, in smaller quantities, etc.

Figure 5-4 shows the growth of truck transport (tons per building value[5]) for all building materials. Implications for these data are not as clear as for those for truck modal split for cement. A general and continuing increase in the weight of building materials hauled by truck per constant building value is observed. As it is unlikely that the total weight of materials per building value is increasing (in fact, lighter materials are probably causing a decrease), this graph may be interpreted as showing increased market share for trucks throughout the period. Our suspicion is that the reduction observed in the late stages of the data may signal the beginning of the maturity for truck penetration of the building materials market.

Figure 5-5 presents a measure of transportation consumption, the amount of truck freight transportation consumed per capita - another S-shaped trend. A logistic curve was estimated for the data, excluding data for 1942 to 1949.[2] Results indicate that 90 percent of the saturation value of 2500 ton-miles per capita was attained by 1973.

The next graph presents truck vehicle miles traveled (VMT) per capita (See Figure 5-6). Upon observation, this trend shows no signs of maturity and because truck ton-miles per capita has slowed, an initial conclusion would be that truck capacity is decreasing. This statement is in part correct because of two factors. First, the definition of truck includes pickups, most of which are used for passenger transportation. Second, due in part to the switch to a services based economy, there are more small delivery (package express, UPS, pizza delivery, etc.) trucks in the fleet. However, there has been no reduction in capacity of over the road trucks which more commonly approach legal weight

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[5]Due to wide building volume fluctuations, some construction data in this chapter have been normalized to the real cost of building output (1967 dollars).

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restrictions imposed by states. Analysis of trucks that haul building materials (larger trucks) would likely show the slowdown in VMT per capita observed in the ton-mile data. Additional discussion about truck definitions is included in the following paragraphs and in sections 5.2.1.2. and 5.2.1.3.

Figure 5-7 shows the average annual miles driven per truck in the U.S. The results, which show a roughly linear upward trend from around 9000 miles in the 1930's to near 13,000 today send a mixed signal. The definition of truck includes many small, passenger and delivery trucks. Figure 5-7 also shows figures for average travel per trailer combination truck after 1964 (*Highway Statistics Summary*, 1987). The trend for these larger trucks remained relatively stable at around 40,000 miles per year until 1976. From 1977, the trend shows a steady increase to about 55,000 miles per year. This value may be approaching a limit given the existing motor freight production set (a highway system where trucks and automobiles must share the same facility, truck technology and design, speed limitations, and current logistical procedures).

5.2.1.2 Truck Performance

In this section, we present the trend in average speed of trucks. The average free-flow speed of vehicles is by no means a wholly adequate performance measure for freight transportation. A more suitable measure would reflect the time required for freight to be delivered from producer to consumer (including all logistic times: warehousing, handling, loading, transfers, etc.). Data such as these, particularly comprehensive regional or national data, are difficult to obtain. Figure 5-8 gives the average speed of trucks on rural highways (non-peak times). Data are not available prior to 1945 as few speed studies were conducted before World War II. Before passage of the 55 mph speed limit law in 1974, speeds increased steadily from 40 mph in 1945 to 57 in 1973. Reporting methods after this date prevent comparability to prior data. There is some question as to the real impact of the speed limit change on actual behavior. However, it is likely that speed limitation would be institutional (speed control laws - 55 mph, 65 mph) or infrastructural (highway design limitations 70 mph, 80 mph) rather than technological (truck performance 100+ mph?).

Again, as a performance measure for freight transport, speed on uncongested rural roads is in itself somewhat meaningless. However, the data were examined as a possible measure of minimum freight transit times.

Average motor freight load is presented in Figure 5-9. Increasing representation of smaller delivery and personal passenger trucks in the mix may be responsible for some of the decrease in motor truck average load. Smaller delivery trucks serve commodities and markets where the optimum shipment size is becoming smaller rather than larger - where frequency is more important than capacity (service, information sectors). Another reason for the slowdown in growth of average load is the 80,000 lbs GVW limit in most states. Although many trucking interests would like to see these limits increased, there are institu- tional, societal and infrastructural barriers. Note that the average load is not intended to indicate a maximum capacity. The motor freight load for empty trucks (backhaul) has been averaged in as zero. What is important is the shape of the development curve.

A logistic model for motor freight average load was estimated. In 1954, this trend reached 90 percent of its saturation level of 6.3 tons. Comparable data were not obtained beyond 1965.

Figure 5-9 also shows the average load for regulated general freight carriers for selected years from 1945 to 1970 and from 1970 to 1987. The trend exhibits an S-shaped growth pattern with maturity indicated by fluctuation around a value of about 13 tons after the early 1970's.

Data for average load of regulated specialized carriers of building materials were also collected. The recent trend for these carriers shows a decrease from 17.8 tons in 1975 to 16.0 tons in 1987 (*Motor Carrier Annual Report*, 1987; Trincs Transportation Consultants, 1976). Although we did not compile data for earlier years, the decrease in average load seems to indicate that productivity gains associated with larger loads were limited to the past.

5.2.1.3 Vehicle Access

This section presents an analysis of the scope of motor freight transport. Data that characterize access to motor freight transportation are not readily available. Today, essentially all addresses in the U.S. are served at least daily by motor carrier, post office,

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package delivery service, etc. Of course, this level of service was not always so. A very interesting analysis would historically examine the frequency, quality, speed, and price of freight service as a function of geographic location (local, regional) and number of individual locations served. As a proxy for motor freight transport access, we use the number of truck registrations per capita (see Figure 5-10). Although the trend shows no indication of maturity, this may be due to the increasing number of small trucks in the truck population. We are interested in freight transport for building materials. In 1982, 86.4 percent of all trucks registered in the United States could be classified as being a pickup, panel, or walk-in truck (*Census of Transportation*, 1982). That figure was up from 65.6 percent in 1963 and only 52.3 percent in 1941 (*Motor Truck Facts*, 1944). Removing these trucks from the total would produce an S-shaped trend that would have reached its saturation value well before 1970 (see Figure 5-10).

5.2.1.4   Infrastructure Development

Concurrent with deployment of motor freight vehicles was development of the highway infrastructure, two components of which were identified for analysis. First, we present data on the amount of surfaced roads in the United States. This includes rural and urban freeways, expressways, arterials, streets, and all other roads. The second measure we use is development of the interstate highway system.

For surfaced roads in the United States, we present two sets of trend data. The first trend shows an S-shaped curve for miles of surfaced roads (see Figure 5-11). After reaching 90 percent of the 3.5 million miles saturation value for surfaced roads (about 1974), few miles have been added to the U.S. highway system.

Figure 5-12 shows the corresponding trend for the percent of surfaced roads in the United States. Although, the total number of miles of roads in the U.S. has grown from 2.4 million in 1900 to 3.9 million in 1985, (an increase of about 50 percent) the percent of paved roads in the same period has grown from less than 5 percent to near 90 percent. Percent of paved roads reached 90 percent of its saturation value in 1973 one year before the t_{90} value for paved mileage.

Figure 5-13 presents data for deployment of the U.S. Interstate Highway system - mileage open to the public. Some pre-existing mileage was incorporated into the present

system. Deployment of this system facilitated intercity freight and passenger transportation. The system was planned from the beginning to consist of approximately forty-two thousand miles of access-controlled highway. The impact of the Interstate on the organization of production, urban development, and the national economy has been extensive. That 90 percent of the planned mileage was completed and open to the public by 1980 is an indication of system maturity.

Today, policies for future directions for highway transportation at the federal, state, and local levels are primarily limited to those designed to foster maintenance of the existing infrastructure and completion of a few costly urban links.

5.2.2 Passenger

We now turn to trends in passenger transportation. Only measures for local or urban passenger transportation were used. Interstate and rural transportation were not considered as scope was limited to transportation system improvements which have enabled reorganization of labor either by allowing 1) access to a large enough job market to warrant specialization, or 2) by providing an adequate labor market for efficient factory production or prefabrication. The categories for passenger transportation are vehicle use, vehicle performance, vehicle access, and infrastructure. Because trucks and automobiles share the road, infrastructure data are not included here. The reader is referred to Section 5.2.1.4. for infrastructure trends.

5.2.2.1 Passenger Vehicle Use

Two sets of data are presented for passenger vehicle use. After the historical trend in urban passenger VMT is examined, miles per automobile per year are given.

Figure 5-14 shows the trend in urban passenger VMT for the period 1936 to 1987. With the exception of declines during World War II and during and shortly after the two energy shocks (1973 and 1979) urban passenger VMT has consistently increased. Because it was not known if urban passenger VMT had reached half its saturation value, a logistic curve was not fit to the data. However, due to increasing congestion in many urban areas, the saturation for urban passenger VMT may not be far off. However, in most small-to medium-sized urban areas there is still plenty of room for increase in urban passenger VMT expansion.

Figure 5-15 shows the trend in miles driven per automobile for the period 1936 to 1987. With the notable exception of a severe decrease due to rationing of gasoline, oil, and tires during World War II, the amount of miles traveled per automobile has remained relatively constant and has fluctuated between nine and ten thousand miles per year since. In reference to the previous graph on urban passenger VMT and total VMT in general, increases in VMT are not due to automobiles being driven more, rather simply because there are more automobiles. When the trend in number of automobiles slows, we expect the trend in vehicle miles traveled to do the same. Later, in this chapter we will look at number of automobile registrations and relate that to its impact on VMT based on the above rationale.

5.2.2.2 Passenger Vehicle Performance

As in truck freight transportation the average speed of automobiles may not be a good measure for the efficiency of the automobile highway system. However, average speed on rural highways under uncongested conditions is a good estimate for the maximum speed of travel given technological, institutional, and infrastructural constraints (see Figure 5-16). In the trend of automobile speed on rural highways, a steady increase is observed from 1945 through 1971. After passage of the 55 mile per hour speed limit law, a reduction of approximately 5 miles per hour on average speed was noted. Since 1975, comparable data have not been available for average speed of automobiles, but the trend for all vehicles shows oscillation around a set point between 55 and 65 miles per hour. As was mentioned for truck transportation, reporting methods may affect the comparability of the data after passage of the speed limit law. However, a limit (saturation value) for speed was expected if not due to institutional constraints such as the speed limit law then due to infrastructural constraints (design speed limits for the roadway) or technological con-straints (the automobile as it is produced). As automobile technology had produced a fleet capable of average speed of 45 miles per hour by 1945, (rural highways), speed limits for urban travel were probably reached by the early years of system deployment. Automobiles of the 1920's and 30's were capable of speeds which would enable them to drive at the limit during uncongested conditions on most urban streets of today.

5.2.2.3 Automobile Access

We approximate automobile passenger transportation access or scope by the trend in automobile registrations per capita (see Figure 5-17). This trend shows no sign of maturity. However, it is reasonable to assume a saturation value of less than one vehicle per potential driver in the population. An estimate for this saturation level might be 0.75 per capita which is roughly the percentage of persons in the United States over the age of sixteen. Using 0.75 as a saturation value, parameters for $\ddot{a}_t$ and t_{50} were estimated by the FIT program. As few cars were produced during World War II, data for 1942 to 1945 were not used in the regression. Results of the FIT program indicate 90 percent of the 0.75 saturation value will be reached by about 2004. However, even a value 0.75 automobile registrations per capita may be high due to the fact that not all drivers over age sixteen will want, be physically able, or be financially able to afford vehicles. This suggests that the 1987 rate of 0.55 automobile registrations per capita may be fast approaching the saturation level.

5.2.3 Summary of Trends in Transportation

Before presenting trends in housing production, we would like to ask if a general conclusion might be drawn from the transportation trends. While some of the measures chosen show rapidly changing trends, many have approached saturation levels (railroads, truck freight share, shipment sizes, roads, and vehicle populations). From the data and analysis presented above, it appears that the highway transportation system has been fully deployed and is fast approaching maturity. If our hypothesis of the strong relations between transportation and production is valid, we would expect to observe the implications of this maturity manifest in reduced productivity in the housing industry. To examine these relations, the following sections present time series data for residential construction and building production.

5.3 Housing and Construction Trends

In this section we examine trends in the production of housing. As mentioned previously, data for the entire construction industry were often more comprehensive than those for housing. Where gaps exist in the information for housing, construction data are supplied.

The data are divided into categories consistent with the transportation section presented above. Construction performance measures include price of inputs, cost or value of output, and productivity. Data are grouped into three divisions: 1) materials supply, 2) labor organization, and 3) total factor productivity.

5.3.1 Materials Supply

Five sets of data are provided to show trends in the cost of material inputs to the construction industry. Figure 5-18 shows the real price of construction materials index (1967=100). The figure shows an upward trend for the entire period 1870 to 1986. This increase indicates either higher cost for equivalent materials or the introduction of new types of more expensive materials. Factors that contributed to price increases include increasing scarcity of resources, as resources for building materials were being depleted. The increasing price of construction materials during a time of transportation development and technological improvement is seemingly counter-intuitive.

Symmetry of some of the trends is suggestive of explanations beyond simple, direct relationships between transportation and building production. Although outside factors may have been involved, substitution of new, higher priced for locally available materials was enabled by improvements in transportation. A more detailed study would be necessary to determine the impacts of quality and changing materials. For example, many of the plastics used in construction were not available before 1920. As standards of living rose, the increases in real prices of construction materials may reflect more expensive consumer choices.

Figures 5-19 through 5-22 show trends in real price of specific construction materials.

Figure 5-19 shows the trend in real price of millwork from 1925 to 1986. The real price of millwork doubled from 1925 to 1955 and thereafter has fluctuated around what appears to be a set point. Why did the price of millwork increase at more than double the inflation rate before 1955? The quality of millwork used in homes is a possible explanation, although it is questionable whether the quality of the product increased during this period.

The Great Depression and World War II occurred during the turbulent period between 1925 and 1955. During the Depression, the price of labor was greatly reduced compared to the price of capital. At the time, millwork was labor intensive. Therefore, during this period millwork prices may be abnormally deflated. During the War, labor became scarce. From this we would expect a higher cost of labor input and a subsequent increase in the real price of millwork. However, before 1955, the manufacture of millwork was being moved from the construction site to factories as prefabrication of housing components became more common.

The replacement of on-site labor by factory labor should have decreased the real cost of millwork. The trend does not bear out this relationship. Our conjecture is that improvements in mill productivity enabled by the reorganization of labor had occurred before the time of observation. This conjecture is supported by William B. Lloyd's *Millwork - Principles and Practices*. The author attributes most of the reorganization of the millwork industry to improvements in transportation (first canal and river and later to rail transportation). The railroad came after the introduction of woodworking machinery and tools during the industrial revolution (Lloyd, 1966).

Because standardization of millwork began early, (1889, with the adoption of the 13/16" standard thickness for pine wood flooring) the industry was probably mature (most productivity improvement had taken place) well before the deployment of the auto/truck highway system.

Prior to industrialization, millwork such as windows, doors, frames, stairs, banisters, moldings, and rails had to be constructed on-site by the carpenter or in a carpenters' shack located near the site. The cost of factory millwork represented by the graph would not reflect the price of on-site carpenter constructed millwork. The cost of this type of site constructed millwork was certainly higher, but data are not available to show the comparative prices.

Figure 5-20 shows the real price of concrete ingredients from 1925 to 1986. The trend is dominated by two regimes before 1945 and during the Depression. The real price of concrete ingredients increased to a maximum around 1932, decreased until the start of World War II, increased slightly during the war, and drastically decreased in terms of real cost shortly thereafter. From a low price in 1947, the real price of concrete ingredients

had rebounded to post-depression levels by 1960, and has since fluctuated around this point. We draw no direct conclusion from this trend relating to transportation. The trend seems to follow construction demand. Since concrete ingredient plants have high fixed costs, this trend may be simply attributed to economies of production scale.

Figure 5-21 shows the trend in real price of douglas fir, an important residential construction component. The real price remained relatively constant until 1967. During the decade of the 1970's the real price of douglas fir increased by a factor of two, then by 1980 to 1982 decreased to previous levels. It appears to be widely fluctuating around a historical average. Perhaps transport improvements once provided increased access to plentiful and cheap supplies (holding prices stable) until resources were depleted. Maturing transport systems have failed to increase access to new sources.

Figure 5-22 shows the trend for real price of all lumber. Before 1935 the price of lumber was relatively constant. Between 1935 and 1950 the price increased by 100 percent and has since oscillated around this value. The lumber industry is transportation intensive (up to 70 percent of total costs directly attributable to transportation and handling). With the improvements in transportation during the first half of this century and in lumber handling machinery since, the real price (of lumber) has been held to the level of 1950. The depletion of local resources of lumber, the only resources available without advanced transportation and handling methods, would have greatly increased lumber price. In the past, improved transportation and lumber handling machinery technologies have enabled the extraction of lumber from previously infeasible remote areas.

5.3.2 Labor Organization

This section examines trends in labor costs for the housing and construction industries. Figure 5-23 shows labor productivity from 1948 to 1976. These data were obtained by dividing the values given for real output by those given for labor input by Kendrick and Grossman (1980). The trend is characterized by a steady, nearly linear increase from 1948 to the late 1960's. During this period, labor productivity increased by a factor of two. After the late 1960's labor productivity has declined (through 1976, the last year for data) losing almost half of the gains obtained in the prior twenty years.

Figure 5-24 shows another measure of labor productivity, construction value per construction worker in real dollars. The trend from 1950 to 1970 is strictly increasing. Before 1950, the data shows wide variations in value per construction worker with an overall increasing trend starting slowly and then increasing more rapidly. After 1970, the data again exhibit wide fluctuations with less of an increase in value per worker. It appears that after 1970, the trend is oscillating around a set point.

Figure 5-25 shows the trend in construction employment per one thousand population. These data are dominated by the impact of recessions and wars between 1910 and 1950. The data are somewhat more stable before and after this period. It is interesting to note that the period of rapid improvement in construction productivity is also that of widely variable construction worker population.

An analysis was performed to identify changes in the organization of building labor in the last 100 years. Six trades were chosen to represent building labor. Because census data do not provide an adequate level of detail, it was not possible to analyze housing independently from all construction. Labor organization was represented by the number of employees in each of the six trades. Trend data were presented per million 1967 dollars of construction value for the years 1880 to 1980. The six representative trades are: brickmasons, carpenters, electricians, painters, plumbers, and roofers.

During the first half of the 20th century, the number of tradesmen per output decreased. After 1950, each of the trades leveled off in employment per output. The period when these trades experienced decline in labor force was the period of rapid deployment of the auto/truck-highway network. There was increased prefabrication of housing and construction components, and increased productivity per worker. After 1950, along with the relatively stable trend in labor force, the highway system matured and construction productivity has decreased.

Figures 5-26 through 5-31 show the trend in numbers of specialized construction-trade workers per constant building value. Figure 5-32 shows the aggregated measure for all six trades per building value.

Figure 5-26 shows the trend in number of brickmasons, stonemasons, and tile setters per million 1967 dollars building value. The trend is decreasing throughout, rapidly at first, then at a greatly reduced rate (becoming almost flat) after 1950.

Figure 5-27 shows number of carpenters per million 1967 dollars building value. This data set shows the same trend as for bricklayers, rapid decrease until after 1950.

Figure 5-28 shows the trend for electricians. The data starts at 1920. Before this period most houses were equipped with little electrical equipment.

Figure 5-29 presents the trend for number of painters and glaziers per million 1967 dollars building value. Again, the trend decreases rapidly until 1950.

Figure 5-30 shows the number of plumbers and pipe fitters per million 1967 dollars building value. The increase from 1910 to 1920 should be attributed to the introduction of indoor plumbing to the majority of newly constructed homes. After 1920, the trend is decreasing indicating higher productivity per tradeworker with a rapid decline until 1950.

Figure 5-31 shows the trend in number of roofers and slaters per million 1967 dollars building value. Although the data fluctuate widely before 1950, an overall decreasing trend is apparent. After 1950 the trend continues with a less rapid decrease.

Figure 5-32 shows the sum of all six specialized trades per million 1967 dollars building value and can be thought of as an approximation for labor productivity in construction. These six trades are the most important and numerous in the residential construction industry. The trend, as anticipated, decreases rapidly until 1950, and thereafter remains fairly constant.

5.3.3 Total Factor Productivity

Some measures which reflect total factor productivity in residential construction and building are identified in this section of the chapter. Figure 5-33 shows total factor productivity in contract construction as calculated by Kendrick and Grossman. With a doubling of productivity in the period 1948 to 1970 and a subsequent reduction of approximately 50 percent of total factor productivity after 1970, the trend closely resembles their findings for labor productivity. This follows from the authors' weighting of labor as 90 to 95 percent of total factor input (TFP estimates were estimated by combining labor and capital inputs in the ratios of their respective shares in gross national income originating in contract construction. The 1948 weights were used for the period 1948 to

1959 (labor = 92.6%), 1959 weights for 1959-69 (labor = 94.7%), 1969 weights for 1969 to 1973 (labor = 92.1%), and 1973 weights thereafter (labor = 93.2%).

Figure 5-34 presents data for capital productivity. The trends show an approximately linear decline from 1948 to 1976 (a factor of two). The figures were calculated by dividing Kendrick and Grossman's data for real output by capital input.

Figure 5-35 presents data for real construction costs per housing unit. The trend can be divided into two basic regimes: a relatively constant level before World War II and a nearly linear increasing trend after 1950. During the increasing period after 1950, real cost per housing unit has increased by a factor of three. Drawing conclusions from this trend is complicated as outputs are not adjusted for size or quality, which have certainly increased since World War II. Unless the output can be adjusted for quality, the improvements in construction productivity (partially enabled by transportation development) cannot be seen in this data.

Figures 5-36 and 5-37 present indices for the cost of building. Figure 5-36 is indexed to 1967 and represents cost of building in real dollars. Figure 5-37 shows the cost of building index (1967=100) in current dollars. The trends closely resemble the trend in Figure 5-35 (cost per housing unit). A period of rapid increase in cost of building spans from the 1910's to 1970. After 1970, the cost of building seems to be fluctuating around a set point.

Figures 5-38 and Figure 5-39 show the cost of residential construction indices. The first figure (5-38) is indexed to 1967=100 in constant dollars. The second figure (5-39) is in current dollars. The trend in real cost of residential construction falls into two regimes. Between 1890 and 1910 cost was relatively constant. After 1910, real cost increased somewhat linearly to three times the 1910 value.

The last data set for construction is presented in Figure 5-40 "Construction Value per Capita" (1967 dollars). The trend shows a twofold increase during the period 1950 to 1970. Before 1950, the trend is variable and slowly increasing. After 1970, construction value per capita widely fluctuates.

5.3.4 Summary of Trends in Housing Construction

Conclusions to be drawn from the construction data are not as strong as those for transportation. Some housing measures indicate declining productivity during years of transportation improvement while others support direct relations between transportation and productivity. To resolve these issues, a case study for more detailed analysis is motivated (see Section 5.5 and Chapter 6).

5.4   Transportation and Housing Construction: Comparison of Trends

The discussion now turns to how the trends identified in the preceding two sections relate, and the first question to be addressed is what can be measured at the level of trend analysis. It is of no practical value to observe that no modern activity can take place without transportation, and that there is complete dependence on transportation. Of practical value is the change at the margin (or incremental change).

The S-shaped behavior of transportation trends send two signals - a flex from flat to ascending and a flex from ascending to flat. The discussion to follow will examine the construction trends in relation to these flexes. Some of the trends do not relate directly, and remarks will be made on possible reasons.

The data presented in the first section of this chapter indicate that the auto-truck highway system is at or near maturity. Although room for growth exists in some areas, potential for development on the order of that of the past is slim.

Examination of the housing trends reveals two basic phenomena, both of which include 1) change throughout the period of auto highway rapid deployment and 2) stagnation after the highway system began to mature. The first phenomenon is the rapid increase in real price of material inputs to and outputs from the construction sector, partly attributable to increases in quality. The second phenomenon is improvement in labor productivity during the first two-thirds of this century and its subsequent decline. For convenience we will refer to these two phenomena as the "increasing quality" phenomenon and the "improved organization" phenomenon.

Before we identify trends to support "increased quality" or "improved organization," we point out that these phenomena are not mutually exclusive. Although some of the "increasing quality" trends do not show it, improved organization and supply technology has had a positive effect. However, data such as the real price of construction

materials do not allow simple identification of the part of the change in price attributable to improved transportation, new technology in equipment, depletion of resources, new choices, higher quality, profit taking, unionization, or other factors contributing to the change. Similarly, the trends supporting "improved organization" and supply do not reveal contributing factors. At the level of the data available and collected, only the net effect of the factors could be quantified.

Now we turn to trend comparison. With the exception of truck VMT per capita, auto registrations per capita, and urban passenger VMT per capita, all the transportation data presented support the conclusion of highway maturity. Accounting for conventional truck definitions, assuming logical saturation value for auto registrations, and forecasting VMT using average miles driven per vehicle, (see trend descriptions, section 5.2), these three trends also support impending or current maturity. Although it is difficult to place a date on this maturity, the measures seem to indicate rapid deployment of the auto-truck-highway system during the 1920's to 1960's.

Now, we organize the housing/construction trends into the respective "increasing quality" or "improved organization" classes.

5.4.1 Increased Quality (Depleting Resources)

Some of the construction housing data presented shows increasing real cost of materials inputs or outputs during a period of improved transportation. Although seemingly counter-intuitive, these trends may be explained by the following: 1) Real cost may be increasing due to the depletion of locally available natural resources. Chief raw materials for housing include lumber, stone, clay, and glass products, fabricated metal products, and some petroleum and plastic components. 2) Real cost of factors could be decreasing (or not increasing as fast as the trends would indicate), but increased demand for higher quality, exotic, or otherwise more expensive commodities may be driving the trends. There are questions of quality and quantity; adjusted for these, factor prices and output costs trends may look quite different.   Housing and construction trends which have exhibited increases in real costs are the real price of construction materials, millwork, and lumber, capital productivity, construction cost per housing unit, and indices for cost of building and cost of residential construction.

5.4.2 Improved Organization

Some of the data collected support correlation of improvements in transportation systems and increased productivity in housing and construction. The housing and construction trends exhibiting direct relations with improved transportation are labor productivity (and construction value per construction worker), the number of specialized and total workers per building value (brickmasons, carpenters, electricians, painters, plumbers, and roofers), total factor productivity, and construction value per capita.

For these series of data, correlation with transportation system deployment may be shown, but causality has not been proven statistically. Possible arrangements of causality were presented in chapter 4: 1) transport improvements led improvements in housing productivity, 2) housing improvements stimulate transportation improvement (feedback, e.g. coal production and rail road, empty truck containers and containerized shipping), 3) transport and housing innovation caused by a common technological innovation, 4) transport and housing improvements occur simultaneously due to a wave of general technological innovations, and 5) housing innovations occur independently of transportation.

Some of the trends presented in this chapter support these hypotheses more than others. While none are conclusive, the trends are suggestive of strong relations between transportation and production.

Many questions remain to be answered, but due to necessary limitations on the scope of this work they cannot be answered here. Future work might include determination of the impact of various factors on the increases observed in cost of construction inputs and outputs.

5.5 Conclusion

This discussion leaves some absence of relations unexplained, and where relations were noted, they were described in a broad brush fashion. A case study is therefore motivated, and the discussion beginning in the next chapter seeks deeper and broader explanations.

Before leaving this chapter, however, we should again remark on the thrust of this study. More could be done within this chapter using statistical analyses of trends and/or introducing additional data or transformations of the data that were presented. For instance, the increased real cost of capital inputs to construction seems counter-intuitive in

a period where transportation services were improving. Some outside factor such as resource depletion might be involved. (More expensive aggregates could have been mined.) Perhaps substitution possibilities enabled by transportation improvements occasioned shifts to more expensive, higher quality inputs. (There may have been a shift from local, poor quality lumber to more expensive, higher quality lumber hauled some distance.)

Exploration of these topics would be interesting and worthwhile. However, the chief thrust of this thesis is on productivity changes from innovations enabled by improving transportation. Topics such as those just mentioned are not pursued in favor of specification and investigation of these productivity relations.

5.6   Figures for Chapter 5

U.S. RAILROAD MILEAGE

$K = 250,000$ miles, $\delta_t = 47$, $t_{50} = 1884$, $t_{90} = 1908$

Source: (*Historical Statistics*, 1975)

Figure 5-1

MOTOR TRUCK FREIGHT

(% of all intercity Freight)

+   Data points not used in regression

K = 24 percent, δ_t = 38 years, t_{50} = 1944, t_{90} = 1963

Sources: (US Congress, 1961), (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-2

SHIPMENTS OF CEMENT TO ULTIMATE CONSUMER

TRUCK MARKET SHARE (by weight)

$K = 88$ percent, $\delta_t = 22$ years, $t_{50} = 1959$, $t_{90} = 1970$

Source: (USDOT, 1979)

Figure 5-3

BUILDING MATERIALS HAULED BY TRUCK

TONNAGE PER MILLION 1967 DOLLARS BUILDING VALUE

Source: (*Motor Carrier Statistical Summary*, 1950-1980)

Figure 5-4

MOTOR TRUCK FREIGHT
(Ton-miles per capita)

+   Data points not used in regression

$K = 2500$ ton miles, $\delta_t = 38$ years, $t_{50} = 1954$, $t_{90} = 1973$

Sources: (US Congress, 1961), (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-5

TRUCK VMT

per capita

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88), (*Highway Statistics*, 1983-88)

Figure 5-6

Figure 5-7

Sources: (*Historical Statistics*, 1975)
(*Statistical Abstract*, 1971-88), (*Highway Statistics*, 1983-88)

AVERAGE SPEED OF TRUCKS

(rural highways, mph)

Source: (*Highway Statistics Summary*, 1987)

Figure 5-8

MOTOR FREIGHT AVERAGE LOAD
(TONS)

□ All trucks

+ Regulated general freight carriers

K = 6.30 tons, δ_t = 28 years, t_{50} = 1940, t_{90} = 1954

Sources: (*Motor Truck Facts*, 1969), (Trincs Transportation Consultants, 1976)
(*American Trucking Trends*, 1979/80), (*American Trucking Trends*, 1985)
(*Motor Carrier Annual Report*, 1987)

Figure 5-9

TRUCK REGISTRATIONS
(per capita)

□ all trucks

+ not including pickups, panels, and walk-ins

Sources: (*Historical Statistics*, 1975), (*Census of Transportation*, 1963-82)
(*Statistical Abstract*, 1971-88), (Highway Statistic, *1983-88*),
(*Motor Truck Facts*, 1945)

Figure 5-10

SURFACED ROADS IN THE U.S.

(thousands of miles)

$K = 3,500,000$ miles, $\delta_t = 56$ years, $t_{50} = 1946$, $t_{90} = 1974$

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88), (Highway Statistics, *1983-88*)

Figure 5-11

SURFACED ROADS IN THE U.S.
(percent of all roads)

$K = 91$ percent, $\delta_t = 59$ years, $t_{50} = 1943$, $t_{90} = 1973$

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88), (Highway Statistics, *1983-88*)

Figure 5-12

U.S. INTERSTATE HIGHWAY SYSTEM
MILEAGE OPEN TO TRAFFIC

Sources: (USDOT, 1979), (*Highway Statistics Summary*, 1987), (Highway Statistic, *1983-88*)

Figure 5-13

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88), (Highway Statistics, *1983-88*)

Figure 5-14

VMT per AUTOMOBILE

(all autos, annual average)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88), (Highway Statistics, *1983-88*)

Figure 5-15

AVERAGE SPEED OF AUTOMOBILES

(rural highways, mph)

Source: (*Highway Statistics Summary*, 1987)

Figure 5-16

AUTOMOBILE REGISTRATIONS
(per capita)

+   Data points not used in regression

$K = 0.75$ per capita, $\delta_t = 85$ years, $t_{50} = 1961$, $t_{90} = 2004$

Sources: (*Historical Statistics*, 1975),
(*Statistical Abstract*, 1971-88), (Highway Statistics, *1983-88*)

Figure 5-17

REAL PRICE OF CONSTRUCTION MATERIALS

INDEX (1967=100)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-18

REAL PRICE OF MILLWORK

INDEX (1967=100)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-19

REAL PRICE OF CONCRETE INGREDIENTS

INDEX (1967=100)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-20

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REAL PRICE OF DOUGLAS FIR

INDEX (1967=100)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-21

REAL PRICE OF LUMBER

INDEX (1967=100)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-22

LABOR PRODUCTIVITY

CONTRACT CONSTRUCTION (1967=100)

Source: (Kendrick and Grossman, 1980)

Figure 5-23

CONSTRUCTION VALUE PER CONSTRUCTION WORKER

(1967 dollars)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-24

CONSTRUCTION EMPLOYMENT
(per 1000 U.S. population)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-25

BRICK/STONEMASONS & TILESETTERS

(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-26

CARPENTERS

(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-27

ELECTRICIANS

(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-28

PAINTERS & GLAZIERS
(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-29

PLUMBERS AND PIPEFITTERS

(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-30

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ROOFERS & SLATERS
(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-31

TOTAL WORKERS - 6 SPECIALIZED TRADES
(per million 1967 dollars building value)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-32

Source: (Kendrick and Grossman, 1980)

Figure 5-33

CAPITAL PRODUCTIVITY

CONTRACT CONSTRUCTION (1967=100)

Source: (Kendrick and Grossman, 1980)

Figure 5-34

CONSTRUCTION COST PER HOUSING UNIT

(1967 dollars)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-35

COST OF BUILDING

INDEX (1967=100) - REAL DOLLARS

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-36

COST OF BUILDING INDEX

(1967=100)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-37

COST OF RESIDENTIAL CONSTRUCTION

INDEX (1967=100) – REAL DOLLARS

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-38

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-39

CONSTRUCTION VALUE PER CAPITA
(1967 dollars)

Sources: (*Historical Statistics*, 1975), (*Statistical Abstract*, 1971-88)

Figure 5-40

5.7   Appendix to Chapter 5 - FIT Program

FIT Program Weighting Scheme

The FIT program written for this research estimates three-parameter logistic equations for time series data. The independent variable (regressor) is time (year). For the dependent variables of interest (measures of transportation system deployment or development) we cannot assume a constant variance over the range of the independent variable (the errors are heteroskedastic). Therefore, weighted least squares (WLS) is preferred to ordinary least squares (OLS) which assumes independent, normally distributed errors. Optimally, instead of minimizing the sum of squared errors, we would minimize the sum weighted by the inverse of the variance. But since we do not know the true variance, we must use a surrogate weight. Based on observations of the raw data, we assume that the standard deviation of the error increases proportionally with the dependent variable. (That is to say that for the transportation data, fluctuations seemed to increase as the S-curve matured.)   The program was therefore written to minimize the sum of (the squared [error divided by the dependent variable]):

$$\text{Minimize } \Sigma \left[(X - X_{est})/X \right]^2$$

FIT Program FORTRAN Source Code

```
C    Dimension Arrays

     DIMENSION T(200)
     DIMENSION X(200)
     DIMENSION XEstimate(200)
     REAL KStart
     REAL KBest
     REAL K
     REAL KDelta
     CHARACTER*12 NameDataFile
     CHARACTER*12 NameOutputFile

C    Open Files

     WRITE (6,100)
```

```
100  FORMAT (' Enter the name of the input file: ')
     READ (5,200) NameDataFile
200  FORMAT (A12)
     WRITE (6,107)
107  FORMAT (/,' Enter the name of the output file: ')
     READ (5,200) NameOutputFile
     OPEN (1,STATUS='OLD',FILE=NameDataFile,ERR=998)
     OPEN (2,STATUS='UNKNOWN',FILE=NameOutputFile,ERR=998)

C    Read data

     READ (1,201) NData
201  FORMAT (I10)
     READ (1,202) KStart,DeltaStart,TimeZeroStart
     READ (1,202) KDelta,DeltaDelta,TimeZeroDelta
202  FORMAT (3F10.2)
     READ (1,203) NKDelta,NDeltaDelta,NTimeZeroDelta
203  FORMAT (3I10)
     DO 10 I=1,NData
      READ (1,204) T(I),X(I)
204   FORMAT (2F10.2)
 10  CONTINUE

C    Echo data

     WRITE (2,213) NameDataFile
213  FORMAT (' Data File = ',A12)
     WRITE (2,208) NData
208  FORMAT (/,' Number of Data Points = ',I10)
     WRITE (2,209) KStart,DeltaStart,TimeZeroStart
209  FORMAT (/,' KStart  = ',F10.2,', DeltaStart  = ',F10.2,
    *', TimeZeroStart  = ',F10.2)
     WRITE (2,210) KDelta,DeltaDelta,TimeZeroDelta
210  FORMAT (/,' KDelta  = ',F10.2,', DeltaDelta  = ',F10.2,
    *', TimeZeroDelta  = ',F10.2)
     WRITE (2,211) NKDelta,NDeltaDelta,NTimeZeroDelta
211  FORMAT (/,' NKDelta = ',I10,', NDeltaDelta = ',I10,
    *', NTimeZeroDelta = ',I10,//)
     DO 11 I=1,NData
      WRITE (2,212) T(I),X(I)
212   FORMAT (' Date = ',F6.0,',    Value = ',F10.2)
 11  CONTINUE

C       Calculate the estimate for X(I) based on the current C       values for the
parameters; calculate the weighted sum C    of errors squared
```

```
      SumErrorSquare=1000000000.
      Delta=DeltaStart-DeltaDelta
      DO 1000 ND=1,NDeltaDelta
       Delta=Delta+DeltaDelta
       TimeZero=TimeZeroStart-TimeZeroDelta
       DO 2000 NT=1,NTimeZeroDelta
        TimeZero=TimeZero+TimeZeroDelta
        K=KStart-KDelta
        DO 3000 NK=1,NKDelta
         SumErrorSquareNew=0.
         K=K+KDelta
         DO20 I=1,NData
          XEstimate(I)=K/(1+EXP(-ALOG(81.)/
     *       Delta*T(I)+ALOG(81.)*TimeZero/Delta))
          SumErrorSquareNew=SumErrorSquareNew+
     *       ((X(I)-XEstimate(I))**2)/X(I)**2
  20      CONTINUE
          IF(SumErrorSquareNew.LT.SumErrorSquare)THEN
           KBest=K
           DeltaBest=Delta
           TimeZeroBest=TimeZero
           SumErrorSquare=SumErrorSquareNew
          ENDIF
 3000    CONTINUE
 2000   CONTINUE
 1000 CONTINUE
        GO TO 999

C    Write an open statement error message if needed

 998  WRITE (6,101)
 101  FORMAT (' error in open statement, check file
     *or filename.')
 999  CONTINUE

C    Calculate the R2 value

      SumX=0.
      SumY=0.
      SumXX=0.
      SumYY=0.
      SumXY=0.
      DO 30 I=1,NData
       XEstimate(I)=KBest/(1+EXP(-ALOG(81.)
     *  /DeltaBest*T(I)+ALOG(81.)*
     *  TimeZeroBest/DeltaBest))
```

```
         SumYY=SumYY+XEstimate(I)**2
         SumXX=SumXX+X(I)**2
         SumXY=SumXY+X(I)*XEstimate(I)
         SumX=SumX+X(I)
         SumY=SumY+XEstimate(I)
  30   CONTINUE
       RSquared=(FLOAT(NData)*SumXY-SumX*SumY)**2/
      *((FLOAT(NData)*SumXX-SumX**2)*
      *(FLOAT(NData)*SumYY-SumY**2))

 C     Write output

       WRITE (2,102) KBest
 102  FORMAT (/,' Upper limit for value = ',F10.2)
       WRITE (2,103) DeltaBest
 103  FORMAT(/,' Years between 10% and 90% of maximum
      *value = ',F6.0)
       WRITE (2,104) TimeZeroBest
 104  FORMAT(/,' Date the value reaches half
      *its maximum = ',F6.0)
       WRITE (2,105) RSquared
 105  FORMAT(/,' R squared = ',F10.2)
       WRITE (2,106) SumErrorSquare
 106  FORMAT(/,' Sum of the weighted errors
      *squared = ',F10.2)

       END
```

5.8   References

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6   Case Study: Drywall Construction

We have discussed the broad relations between transportation improvement and production in the housing construction sector. However, the sweeping view prohibited us from examining the impact of transportation on the specific details of production. To narrow to details, we will identify a particular innovation in housing construction and trace its development, seeking a better understanding of the role of transportation.

This chapter is organized as follows. First, the reasons for selecting drywall construction for case study are presented. After a brief discussion of the history of drywall construction, we follow a method outlined by Fisher and Pry (1971) to model the substitution of wallboard for plaster using a logistic equation. The relations between transportation system development and housing production are analyzed using the substitution as a case in point. Trends identified in the preceding chapter which reflect improvements in passenger (labor) and freight (building material) transportation are correlated with the adoption of the drywall construction innovation. A discussion of industrial location presents an example of the impact of transportation system development on the spatial organization of production. Finally, we calculate the benefit of drywall to residential construction. By estimating the influence of truck transportation on the substitution of wallboard for plaster, we are able to approximate the savings to residential housing production enabled by the marginal improvement in transportation services from rail to truck.

6.1   Identification of Candidates for Case Study

Several housing production process innovations of the past exhibit potential for useful case studies. Examples are stick-building (balloon framing, western framing), premanufactured components (e.g. window and door units, trusses, wall panels), and prefabrication (e.g. manufactured or panelized housing).

Factors involved in the selection of the case innovation chosen include: 1) scope - because nationally aggregated data are more accessible (regional or firm specific

production data are often not reported to public agencies to protect company confidentiality), the innovation should have a national scope, 2) magnitude - we are interested in product/process innovations which enable more-than-marginal improvements (not pseudo-innovations), 3) availability of data - as building data are sparse or incomplete prior to the late nineteenth century, innovations which began their life cycle after that period are desired, and 4) process - to facilitate examination of both freight and passenger transportation relations, the innovation should have process implications for both materials supply and labor organization.

The invention of plaster board by Augustine Sackett in 1895 and the subsequent substitution of drywall construction for the lath and plaster (wet construction) method was identified as the appropriate innovation for case study. Shortly after the introduction of gypsum plaster board, advantages of drywall over plaster and lath caused builders to adopt the new product and wall finishing method in many locations throughout the United States. Data are available for production statistics showing the substitution of drywall for plaster.

The impact of drywall construction on the building industry has been important. Today, the cost of drywall installation is roughly one-eighth the cost of plaster and lath,[6] and this cost comprises 5 to 15 percent of the cost of residential housing, depending on type (Franc, 1987).

As drywall was introduced in 1895, and because the U.S. Geological Survey and the U.S. Bureau of Mines have since published annual statistics on the gypsum industry (*Minerals Yearbook*), data are available for study of the impact of the drywall innovation.

Finally, the adoption of the drywall method as the standard for residential construction in the United States has impacted both labor and materials supply. On-site specialized, higher paid labor has been replaced by 1) lower skilled labor and capital in

---

[6]Including subcontractor's overhead and profit, the average cost for plaster and lath in place is around $40.00 per square yard. The average cost of gypsum wall board (1/2") installation (including hanging, taping, and texturing) is about $5.40 per square yard (Calculated from data in [Saylor, 1987]).

highly automated wallboard plants and 2) a smaller and lower paid on-site force of drywall installers.

At the beginning of this century, crude gypsum was mined, crushed and calcined[7] into plaster at the mine and then shipped by water or rail to building sites. Gypsum production took place in about seventeen states. Wooden lath was produced at lumber mills located near timber sources. Today, plaster and lath materials have been replaced by wallboard produced at plants located near consumption centers. The plaster from which the board is made has been calcined at another location. Although plaster mills are still located at domestic mines, an important and growing number of mills import crude gypsum from distant or overseas sources.

As an introduction to this important innovation, the next section presents a brief history of the replacement of lath and plaster by gypsum drywall in residential housing construction.

6.2   History of Drywall Construction

Crude gypsum is a naturally and widely occurring mineral. In 1900, 86 percent of crude gypsum produced was calcined into plaster of paris. Most of the plaster of paris was used as building plaster (stucco, cement plaster, flooring plaster, hard finish plaster, etc.). The remaining 14 percent of crude gypsum was sold primarily for agricultural purposes. However, a steadily increasing quantity was being used as a retarder in Portland cement.

In 1916 the cost for producing a ton of plaster were: <u>Mining</u>, $0.75 (labor, explosives, haulage to mill, pumping, royalties, etc.); <u>Milling</u>, $0.90 (labor and power for crushing, drying, grinding, calcining, sacking); <u>Shrinkage</u>, $0.15 (Loss of water, dust, conveyors); <u>Fuel</u>, $0.45 (For drying and calcining); <u>Repairs/Supplies</u>, $0.85 (alterations to

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[7]Calcining is the process of heating crushed gypsum to drive off combined water. The resulting product is plaster of paris, which, when mixed with water forms a workable paste that hydrates to a solid, rock-like state.

machines and buildings, lubricants, retarder, sacks); Overhead, $1.00 (administration, selling). The total cost per ton was $4.10 per ton. (*Minerals Yearbook*, 1916)

In 1917, the cost of building a mill to calcine 25 tons of gypsum per day was $15,000 ($600 per ton/day). In 1927, the cost of a plant with capacity of 80 tons per day increased to $100,000 ($1,250 per ton/day). The 80 ton per day plant could produce stucco plaster for $5.75 per ton. A much larger (500 ton per day) plant could reduce the cost to $5.18 per ton. (*Minerals Yearbook*, 1917)

The technology for gypsum board production was developed by the early 1900's, the product's patent having been granted in 1895. The introduction of wallboard, however, was an incremental product innovation. Its introduction was incremental because the manufacture of wallboard was simply the combination of existing technologies (combining processes of the paper and plaster industries) to produce a new product.[8] Wallboard enabled a process innovation in the building industry, drywall construction.

In the early going, incremental changes are accepted by industry conservatives if the changes do not initially appear to threaten existing methods of production. This was the early-on case for wallboard. The following account mentions the production of gypsum lath, an early use for gypsum board technology:

"A large part of the structural plaster now produced is used in specially prepared conditions that appeal to the building on account of their convenience. A plaster board is pressed from plaster interlaminated with sheets of thin cardboard or wood. This plaster board is... nailed directly to the studding in place of lath, and receive(s) a coat of wall plaster directly on its outer surface." (*Minerals Yearbook*, 1910)

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[8]Gypsum board is made by spreading plaster paste between two sheets of paper or other suitable covering. The plastic mass is passed through rollers to achieve the proper thickness. The edges are made true by folding one sheet of the paper over the other. After initial hydration, the boards are cut and then cured further to permit conventional handling.

Initially, gypsum board substituted for only lath, and presented no apparent threat to skilled labor. However, as wallboard began to be used as a replacement for lath and plaster, local plastering contractors presented organized opposition to use of the product.

In 1923, at a meeting debating whether gypsum wallboard would be permitted in Toronto, the Toronto Plasterers Association argued that wallboard was less fire resistant than plaster and lath. They claimed that wallboard joint filler would fall out, that wallboards were subject to breakage and were harder to repair than plaster.

In response, a letter from the Gypsum Industries Chief Engineer replied:

"As was admitted at the meeting, the contracting plasterers are afraid that recognition of, and economies incidental to the use of incombustible wall board, will tend to a curtailment of the plaster business, from a labor point of view, because gypsum wall boards can be erected satisfactorily by carpenter labor." (Contract Record and Engineering Review, 1923)

The Gypsum Industries' letter also disputed the contractors' claims of poor fire resistance and lack of structural integrity provided by wallboard, and related the advantages of labor savings and quality control in the prefabricated product.

The plasterers eventually lost the debate as wallboard was adopted throughout the building industry.

Wallboard was a product innovation which led to an important process change in building (particularly residential). During its rapid growth phase, drywall substituted for plaster and lath (by 1917, hundreds of thousand of gypsum boards had found a niche for use in place of plaster and lath for the interiors of temporary war buildings). Also during the rapid growth phase wallboard was standardized (in 1917, gypsum boards were first made in large sizes (4' x 10') to facilitate rapid covering of large areas. On site laborers (plasterers) were replaced by factory capital and labor and a smaller on-site force (drywall installers).

Today, gypsum is mined in 21 states by 39 companies. In 1985, 17 percent was used in the manufacture of Portland cement, 6 percent in agriculture, 2 percent calcined into

building and industrial plasters and 74 percent calcined and used for prefabricated building products. Since the early 1920's, the US Gypsum Corporation has been the largest producer of gypsum products. SHEETROCK (TM) is now used in virtually all residential construction.[9]

6.3   A Substitution Model

This section presents the application of a technological substitution model to data collected for drywall and plaster and lath construction. The model chosen was first presented by J.C. Fisher and R.H. Pry in *Technological Forecasting and Social Change* (1971). We will use terminology consistent with that used in the discussion of the logistic growth model presented in Chapter 5.

The product life cycle from introduction to maturity can be modeled by a three-parameter logistic equation which produces the familiar S-shaped curve. The functional form of such a model may be given as:

$$X(t) = \frac{K}{1 + \exp(-\acute{a}t - \hat{a})} \qquad (1)$$

Where:

$X(t)$ = the value of the dependent variable at time (t) (plaster or wallboard production for a given year)

K = the saturation value for the dependent variable X (total amount of plaster or wall-board)

$\acute{a}$ = a parameter controlling the rate of growth

$\hat{a}$ = a parameter positioning the function in time

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[9]SHEETROCK (TM) is the brand of wallboard produced by the U.S. Gypsum Company. The name substitutes for wallboard on the job site.

The equation may be normalized by setting $X(t)/K = f(t)$. This reduces the number of parameters to two if K is known. In our case, we have simple substitution of one commodity (wallboard) for another (plaster). The saturation value K is the size of the market, and $f(t)$ and $1-f(t)$ represent market shares for wallboard and plaster, respectively.

Annual statistics for the production of gypsum and gypsum products were obtained from the U.S. Bureau of the Mines' *Minerals Yearbook*. As a measure of the magnitude of plaster and lath construction, figures for production of building plaster were tabulated. The definitions for building plasters changed over the time of interest. Definitions used included: stucco, plaster of Paris, Keenes cement, prepared finishes, and neat, base-coat, molding, sanded, fibered, insulating, and mixed plasters. Although wallboard does not directly substitute for all of these plaster applications, those which it does not replace comprise only a small fraction of the total. Plaster used for partition tiles or for other tiles or blocks was not included. Production figures were given by weight (in tons).

Figure 6-1 presents data for production of plaster and wallboard from 1921 to 1985 in tons per building value (1967 dollars deflated by CPI)[10]. Output was normalized to building value because of the wide variation in building volume over the time of interest. Measures more appropriate for comparison of the two commodities may be specified (e.g. square feet of wall/ceiling covered or number of homes built using each product). However, due to the availability of data, weight was chosen as the comparison measure. We assume that the weight per square foot for plaster and wallboard has not changed during the time of interest. Systematic error is therefore limited to the estimation of total market size (plaster and wallboard). If we assume one ton of wallboard replaces one ton of plaster, market shares may be computed.

Normalizing the data by using $f(t) = X(t)/K$, we used ordinary least squares to estimate the parameters of the logistic model (Figure 6-2). Data for 1942 to 1945 were not used in the regressions as the production of plaster and plaster products was distorted due

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[10]All figures for Chapter 6 are presented in Section 6.6.

to requirements for temporary buildings during World War II. Resulting parameters are: t_{50} = 1950 (time at 50 percent substitution = $ß•ä_t/4.394$) and $ä_t$ = 43 years (time between 10 and 90 percent wallboard substitution = $4.394/á$). The time at 10 percent of wallboard market penetration was calculated to be 1928. The R^2 value for the regression was 0.979.

Drywall construction took 33 years to penetrate 10 percent of the plaster and lath market (1895 to 1928). The substitution of gypsum wallboard for plaster and lath then proceeded at a rapid pace, reaching 50 percent in only an 22 additional years (1950). Wallboard had attained ninety percent market saturation by 1972.

Graphical interpretations of the analysis presented above are given in two figures. Figure 6-3 shows market shares (actual and estimated by the model). The trends for wallboard growth and plaster senescence both exhibit the familiar S-shape. Figure 6-4 shows the application of the model to estimate the production of wallboard and plaster from 1921 to 1985 given total demand (for both).

6.4 Transportation Relations

An important impact of transportation development on production concerns industrial location and market area. New, capital intensive industries require large markets to get started (either large, sparse markets or small dense ones). For the case of prefabricated gypsum products, data to show location of production are difficult to obtain. In 1915, 12 of 69 plaster plants made gypsum wallboard, in 1919, 24 of 54, and in 1928, 28 of 53. The trend is from a few locations of production serving large areal markets to many production points located near consumers. The S-curve trend in market penetration begins as a few consumers in widely dispersed regions slowly adopt the product or idea.[11]

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[11]Communications development is also very important. (See the comment on Schmookler's findings given in Chapter 4.) With only "word of mouth" communication, products or ideas are disseminated at a slow rate. Local markets are saturated before regional or national penetration begins. With rapid or instantaneous information, adoption on a regional or national level occurs here and there, with no great disparity of penetration stage between regions. Here we refer to com-

Transportation must be available to supply a suitable market area if innovations are to be successfully adopted. In the early stages, production takes place at a few locations near the sources of raw materials. As markets intensify, production for a smaller geographic market is feasible.

As the market and production continue to grow, more firms enter and create competition. Production facilities are relocated nearer demand centers. Raw materials are shipped from distant sources via inexpensive bulk transport and finished goods, with higher freight rates, are quickly delivered over the shorter distances from producer to consumer.

Whether the production facilities will be located close to raw materials supply or consumers is also determined by the nature of the product. If the finished product has a higher transportation cost than the sum of transportation costs for its raw material inputs, given adequate market density, production facilities should be located close to the consumer.

Similarly, if production processes are labor intensive, production facilities must be located near sources of labor, often near consumers. Some production processes must be located near the consumer. (Ultimately, the house must be erected where the consumer will live).

Conversely, if transportation costs for raw materials, labor, or energy inputs exceed transportation costs for the finished product, production centers locate near input sources. Transportation costs for inputs may be more expensive than transportation costs for outputs due to several factors: 1) raw materials used in production may be used up in the production process by conversion (e.g. fuel to exhaust gases), reduction (e.g. extraction of enriched ores from earth), or waste, 2) finished products may be more easily handled in

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munications within an industry, which is not the same as communications technology (telephones, radio, etc.) Each industry has its own rate of diffusion for innovation; the construction industry has been characterized as having a particularly slow rate (on the order of 15 years [Construction, 1988]).

their processed state (e.g. meat, lumber), 3) inputs may be used only temporarily then recycled (e.g. power generation cooling water), and 4) inputs may not be capable of being transported (e.g. lands suitable for growing certain crops).

Returning to our drywall example, the following quote relates the above discussion of industrial location to the location of gypsum products production facilities:

"All the new plants built or under construction during 1928, with one exception, are near the markets they are to serve and are supplied with crude gypsum from distant sources by cheap water transport. This is in contrast to the older practice of building the mills at the mine or quarry and shipping the finished products long distances at relatively high freight rates. The market areas for individual plants are becoming more and more restricted as new plants are being built at large consuming centers. As a result of the geographical concentration of markets, however, the individual plants are tending to expand the variety of their products and thus operate with full working complement the year round. Consequently, there will be no off season, as experienced now, because as one product has its off season another will take its place." (*Minerals Yearbook*, 1928)

Before the 1920's, much attention had been given to efficiency of production and not much to market distribution in the plaster industry. In 1929, the industry began to relocate near consumers.

"At present (1923) the location of gypsum products plants with reference to consuming markets necessitates, in some instances, exceptionally long freight hauls ... This condition is the natural result of erecting at the most likely deposits of gypsum, plants that can produce far more than the nearby territory can possibly absorb. Numerous plants, though erected at very good deposits of gypsum, have had to close down indefinitely..." (Bureau of Mines, 1929)

Figure 6-5 shows the market areas for gypsum products in 1929. Note the long supply distances from plants to consuming states. Gypsum plaster was shipped in sound box cars. That year, freight rates for gypsum plaster hauled in 100 pound bags averaged

one cent per ton-mile. Wallboard, which sold for three times the price of plaster (by weight), carried a freight rate of about one-and-one-half cents per ton-mile (Bureau of Mines, 1929). Wallboard and other prefabricated gypsum products were shipped in box cars and required only nominal shoring to keep the material in place.

Figure 6-6 shows the geographic distribution of gypsum mines and processing plants in the U.S. in 1941 (*Minerals Yearbook*, 1941). Although plants were still located at mines, note the proliferation of gypsum products plants near population (consumption) centers. By 1972, the average (median) distance of wallboard shipments from point of production to point of consumption had been reduced to 167.5 miles (Williams, 1976B).

Industrial relocation occurs during the early and rapid growth phases of product market penetration. Because plaster was already a mature product at the time (it had saturated its market), the relocation mentioned in the 1941 *Minerals Yearbook* article may be attributed to the introduction of manufactured gypsum products, chiefly wallboard.

At the time of wallboard's introduction, rail and water transportation systems were mature. By 1917, shipping supported the export of plaster board from the U.S. The largest importers were England, Canada, Cuba, Argentina, Chile, and Australia.

Gypsum mills were often built near railway branches, connected by short spurs as availability of transportation services played an important role in the location of gypsum production facilities.[12] In 1913, in Oklahoma, "Gypsum deposits adjacent to the railways were limited." (*Minerals Yearbook*, 1915) Consequently, the abundant gypsum deposits of that state were not exploited early on.

The railroad and river barge enabled the relocation of plaster production centers close to major domestic consumption markets. These technologies were well suited to the transport of crude gypsum or plaster, but because wallboard damages more easily and is a

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[12]As fuel costs comprised only about 10 percent of plaster production costs, availability of fuel played little part in the location of gypsum products plants. In 1910, 55 plants used coal, 13 used oil, and 2 used wood as fuel. Plants used local fuels; oil burning plants were located in Texas, Arizona, California, Oklahoma, Kansas, Nevada, and Washington.

higher valued commodity than plaster, it was more economical to transport the raw material longer distances.[13]

The price of gypsum and gypsum products has always varied greatly with location. Early references were made in *Minerals Yearbook* (1927) to this variation. In 1927, ground gypsum (raw material) prices ranged from $4.00 per ton in Ohio to $10.50 per ton in Seattle.

Engineering News Record (ENR) reports statistics on building material prices for 20 major U.S. cities. In June of 1988, the price of 1/2" gypsum plaster board ranged from $76.00/MSF in Dallas to about $208.00/MSF in Baltimore (ENR, 1987).

The cost of transporting gypsum products by truck is on the order of $0.03/MSF per mile (1,778 square feet per ton and $0.05 per ton-mile). Gypsum drywall purchased in Dallas and shipped 4800 miles at this price would still sell for $208.00/MSF, the price in Baltimore (only 1435 miles from Dallas). However, transport costs are not the only factor in the increased cost of the material by location. Other factors such as marketing, distribution, labor and overhead costs contribute. It is beyond the scope of this research to investigate all of those factors. Opportunities for significant cost reduction do seem to be presented, however, by the large disparity in regional prices.

The time scale for substitution of wallboard for plaster coincided with the deployment of the truck-highway system. By 1929, the motor truck had replaced, to a considerable degree the railroad in short-haul shipments (Bureau of Mines, 1929).

The truck had two important impacts on the production of wallboard. The first impact was an increase in wallboard market potential as trucks could reach nearly any location where a house was to be built. The second impact was an improvement in the quality and frequency of freight service. The truck was well suited for handling the

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[13]During the early 1900's, wallboard sold for $30 per ton. Plaster sold for about $10 per ton (*Minerals Yearbook*, 1901-1929)

finished product. A truckload was often a more efficient size for delivery of wallboard to builder supply yards.

In order to receive any advantage of shipping by rail, dealers must order shipments in carload lots, but they sell to builders in small quantities. As a rule, dealer capital and space are limited, and they can not tie them up with large supplies of wallboard. Trucks were better suited to handling the easily damaged product. The 1972 Census of Transportation reported that 82 percent of gypsum wallboard was delivered by truck, only 17 percent by rail (Williams, 1976B). Time series data for mode split are not available.

Shipments of cement to ultimate consumers (truck market share) were given in the preceding chapter (see Figure 5-3). The production of cement is similar to the production of plaster (both are mined, crushed, and heated to produce a cementatious product). Although data for plaster shipment mode split were not available, we may expect an S-shaped trend of truck-for-rail substitution similar to that observed for cement.

Wallboard is somewhat awkward to handle without loading equipment. Although the railroad could supply products to building material yards, it was the truck and portable loader (portable crane or fork lift) which enabled efficient delivery from supply yards to the building site. However, because drywall was an important improvement in construction technique, the substitution of wallboard for plaster would have proceeded, even without the development of the truck-highway system.[14] Remaining questions are: 1) at what rate, and 2) to what extent would wallboard have replaced plaster and lath without improvements in transport service?

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[14]The Fisher-Pry model is based on the assumption that once a substitution has progressed as far as a few percent, it will proceed to completion. In our case, the substitution of wallboard for plaster had surpassed 10 percent by 1928 when truck transportation was just getting its start. (See Chapter 5 for truck-highway system growth trends. Our analyses place the date for 10 percent of truck system deployment between 1923 and 1950, depending on the performance measure used.)

6.5   Quantification of Innovation and Transportation Related Benefits

We have observed that over the last 70 years or so, wallboard substituted for plaster. Because wallboard and plaster/lath are relatively direct substitutes, price advantages given availability can be taken as the motivation for substitution.

Transportation impacts price through direct transportation costs (logistics) and indirectly by 1) classic concepts of transportation contribution to production (access to resources, specialization of production and consumption, scale and scope, and agglomeration), and 2) contributions to Schumpeterian process changes (enabling new processes, basic innovations).

Because of the scale of this study (and data limitations), we make several rather sweeping assumptions to estimate the social savings of truck transportation to the drywall innovation. These assumptions will, no doubt produce errors in the actual amount of savings calculated, but the results will be sufficient for demonstration.

First, we assume a savings represented by the adoption of drywall in the average house. The cost of drywall represents about five percent of the cost of the average new house, and plaster and lath costs about 8 times as much. Assuming that the average new house costs $50,000 (conservatively low), the savings are calculated to be $17,500 (today's money). In addition, we ignore elasticity -- the demand for higher priced, plastered homes would be less than for lower priced, wallboard homes.

It is important to say again here that substitution of drywall for plaster would have taken place even without the deployment of the truck-highway system. Many other changes were taking place that also enabled the wallboard innovation (improvements in rolling, papering, and drying processes, for example). The question is: What are marginal changes in transportation, such as those represented by new systems, worth to production? It is appropriate to say that improvements in transportation will at least change the shape (rate, saturation level) of the substitution process.

Therefore, we assume that had the truck-highway system not been deployed, the substitution of drywall for plaster would have proceeded less rapidly (say, $\ddot{a}_t$=60 years

instead of $\ddot{a}_t$=43 years) and to a saturation value of less than 100 percent (say, 90 percent).[15] Figure 6-7 shows graphically how transportation development might change the curve for wallboard market penetration.

A three-parameter logistic equation for the observed substitution of wallboard for plaster (percent) can be specified using the parameters from the above regression:

$$X(t)_T = \frac{100}{1 + \exp(-0.102t+199.28)}$$

and assuming no deployment of the truck-highway (rail system only):

$$X(t)_R = \frac{90}{1 + \exp(-0.087t+171.65)}$$

The savings obtained by the substitution of wallboard for plaster in any given year are given as:

$$X(t) \cdot \$17,500 \cdot U$$

where U is the number of housing units produced that year, and $X(t)=X(T)_T$ for the observed data (with the truck-highway) and $X(t)=X(T)_R$ for our hypothetical case of no truck deployment). The savings due to the marginal improvement in transportation can be calculated as the savings with the truck $[X(t)_T \cdot \$17,500 \cdot U]$ minus the savings without $[X(t)_R \cdot \$17,500 \cdot U]$. Summing these savings from the early years of substitution to the present gives the portion of social savings provided by the drywall innovation attributable to transportation improvement (trucks). Based on our assumptions, we calculate the current yearly value of the social savings attributable to trucks for just this one housing innovation to be $3.8 billion, and the savings since 1921 to be $152 billion (1987 dollars). See the Appendix to Chapter 6 for data.

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[15]The numbers for $\ddot{a}_t$ and K were chosen for demonstrative purposes only. Sensitivity analysis would be a useful exercise.

In 1987, the U.S. invested about $67 billion in roads. About 40 percent of that was for truck related costs ($27 billion). Although wall board use is not the only activity affected by truck transportation, the observation that efficiencies from the extensive use of wallboard (above the level if only rail transport were used) are about fourteen percent of the highway costs attributed to trucks in 1985 gives a sense of the comparative magnitude of what we are discussing.

GYPSUM PRODUCTS PRODUCTION

(tons per building value – million 1967 dollars)

PLASTER   WALLBOARD

Source: (*Minerals Yearbook*, 1901-85)

Figure 6-1

GYPSUM WALL BUILDING PRODUCTS

SUBSTITUTION OF WALLBOARD FOR PLASTER (by weight)

□ PLASTER   ▽ WALLBOARD

+ PLASTER DATA NOT USED FOR REGRESSION
x WALLBOARD DATA NOT USED FOR REGRESSION

Source: (*Minerals Yearbook*, 1901-85)

Figure 6-2

GYPSUM WALL BUILDING PRODUCTS

MARKET SHARE (by weight)

□ PLASTER   ∇ WALLBOARD

+   PLASTER DATA NOT USED FOR REGRESSION
x   WALLBOARD DATA NOT USED FOR REGRESSION

Source: (*Minerals Yearbook*, 1901-85)

Figure 6-3

Figure 6-4

GYPSUM PRODUCING AND CONSUMING STATES, 1929

LEGEND:

• Producing plants
o Indicates states to which
  products are shipped

Source: (Bureau of Mines, 1929)

Figure 6-5

LOCATION OF GYPSUM PRODUCTION FACILITIES, 1941

LEGEND
- • MINE
- ○ UNCALCINED-PRODUCTS PLANT
- □ UNCALCINED-& CALCINED-PRODUCTS PLANT
- ⊕ MINE & UNCALCINED-PRODUCTS PLANT
- ■ MINE & UNCALCINED-& CALCINED-PRODUCTS PLANT

Source: (*Minerals Yearbook*, 1941)

Figure 6-6

Figure 6-7

6.7 Appendix to Chapter 6

Data for analysis of drywall innovation transportation improvement related benefits:

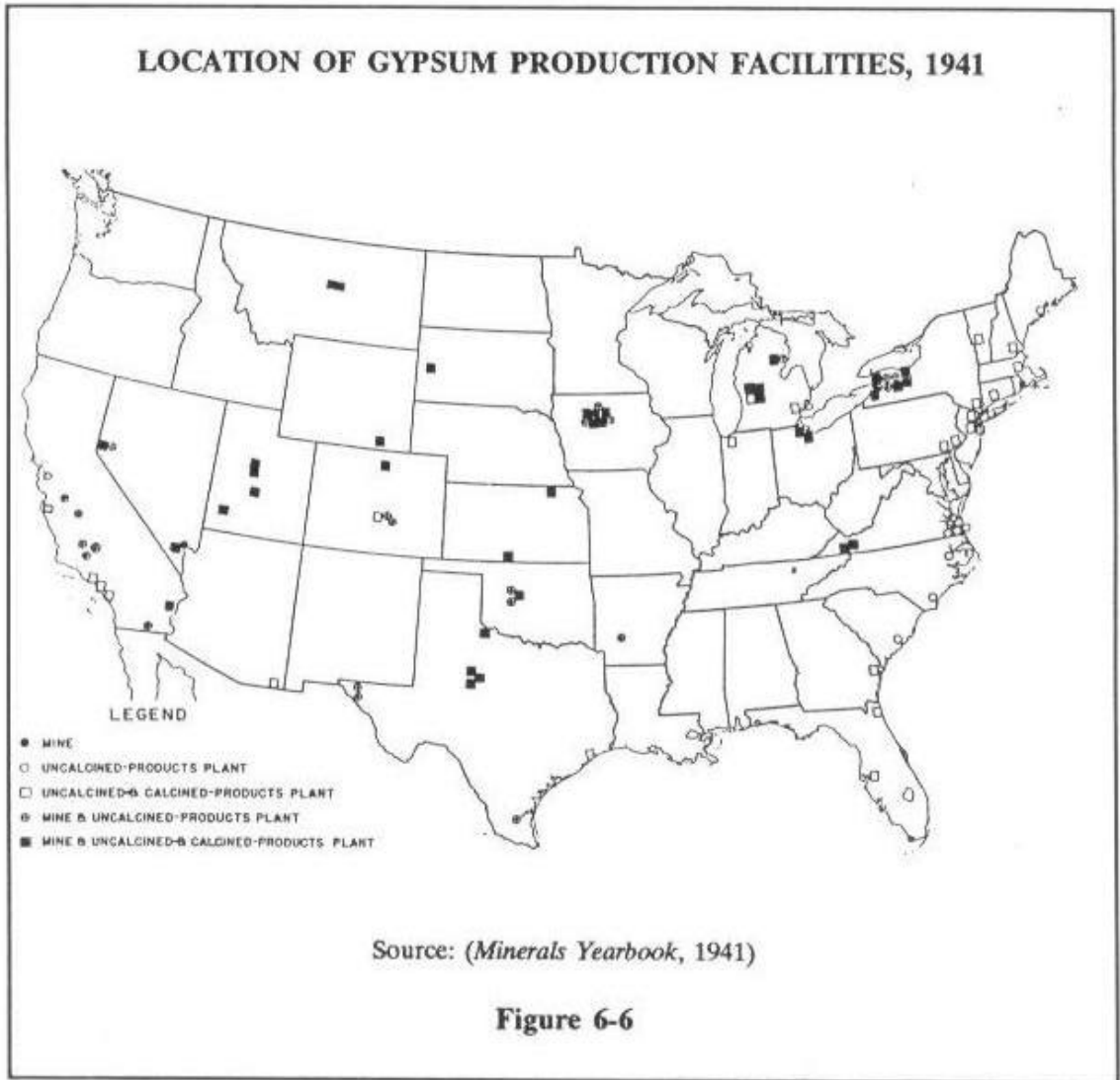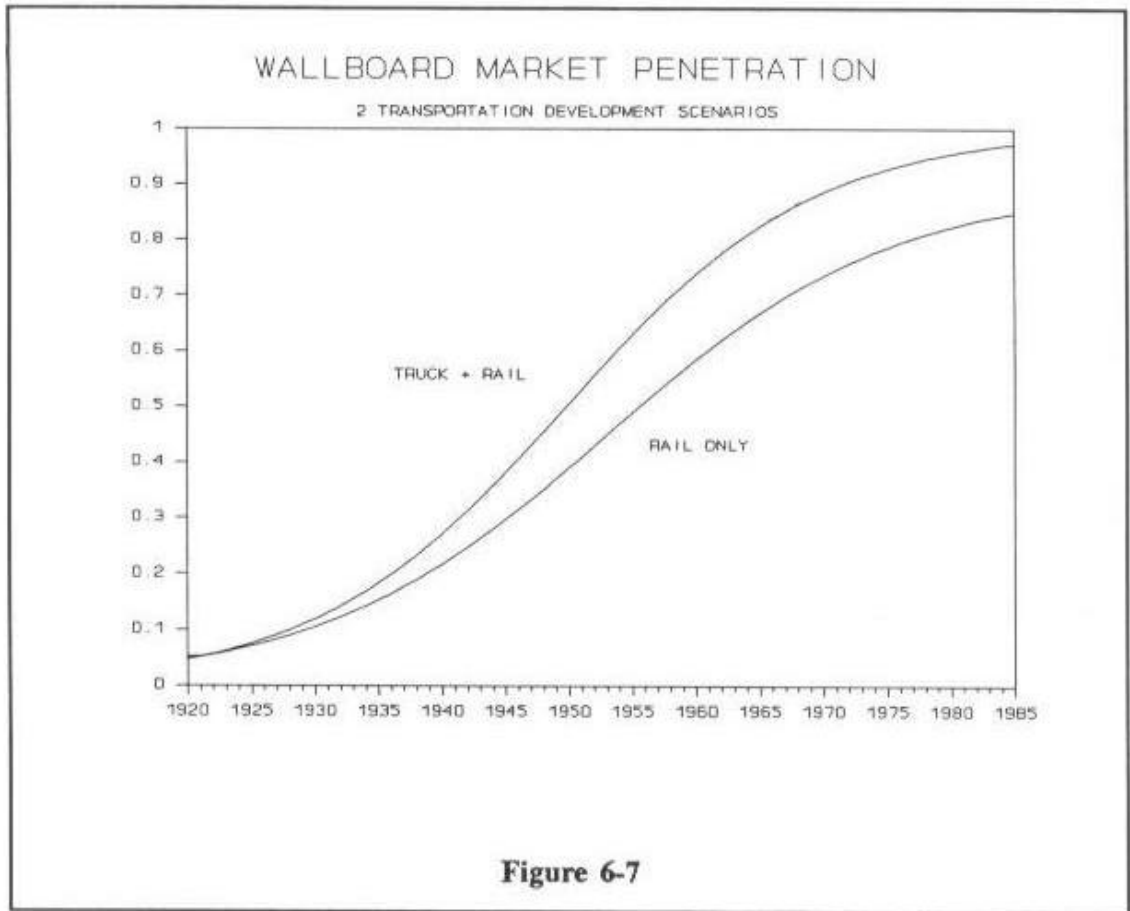| Date	Wallboard Market Penetration (ACTUAL)	Housing Starts (thous)	Wallboard Share (Best fit)	Wallboard Share (Predicted no Trucks)	Benefit (Truck over rail)
1921	4%	449	5%	5%	$6,693,481
1922	5%	716	6%	6%	$20,715,408
1923	7%	871	6%	6%	$39,464,934
1924	12%	893	7%	7%	$57,422,394
1925	11%	937	8%	7%	$80,757,635
1926	13%	849	8%	8%	$94,453,960
1927	11%	810	9%	8%	$113,237,278
1928	15%	753	10%	9%	$129,614,009
1929	18%	509	11%	10%	$106,153,123
1930	17%	330	12%	11%	$82,290,935
1931	17%	254	13%	11%	$74,894,767
1932	17%	134	14%	12%	$46,270,824
1933	18%	931	16%	13%	$37,286,867
1934	17%	126	17%	14%	$58,205,181
1935	15%	221	18%	15%	$116,794,924
1936	15%	319	20%	16%	$191,599,921
1937	13%	336	22%	18%	$227,934,433
1938	15%	406	23%	19%	$309,227,976
1939	15%	515	25%	20%	$437,876,908
1940	17%	603	27%	22%	$569,161,764
1941	24%	706	29%	23%	$735,754,080
1942		356	31%	25%	$407,441,475
1943		191	34%	26%	$238,806,465
1944		142	36%	28%	$192,945,712
1945		326	38%	30%	$478,914,392
1946	44%	102	34%	32%	$1,616,554,435
1947	44%	1268	43%	33%	$2,144,427,307
1948	45%	1362	46%	35%	$2,452,865,672
1949	47%	1466	48%	37%	$2,797,629,520
1950	46%	1952	51%	39%	$3,928,104,526
1951	50%	1491	53%	41%	$3,148,858,797
1952	54%	1504	56%	43%	$3,317,913,297
1953	56%	1438	58%	45%	$3,298,659,862
1954	58%	1551	61%	47%	$3,683,229,431

1955	59%	1646	63%	49%	$4,029,263,010
1956	59%	1349	65%	51%	$3,389,978,477
1957	59%	1224	67%	53%	$3,145,153,056
1958	65%	1382	70%	55%	$3,617,520,833
1959	68%	1554	72%	57%	$4,129,044,964
1960	69%	1296	74%	58%	$3,483,707,994
1961	73%	1365	76%	60%	$3,700,349,122
1962	75%	1492	77%	62%	$4,067,074,518
1963	77%	1635	79%	64%	$4,469,514,689
1964	79%	1561	81%	65%	$4,268,717,496
1965	81%	1510	82%	67%	$4,121,374,853
1966	81%	1196	84%	68%	$3,251,477,631
1967	83%	1322	85%	70%	$3,573,323,601
1968	85%	1545	86%	71%	$4,145,320,680
1969	88%	1500	87%	72%	$3,989,280,452
1970	89%	1469	89%	73%	$3,867,830,990
1971	90%	2085	90%	75%	$5,429,284,767
1972	92%	2379	90%	76%	$6,121,328,976
1973	93%	2057	91%	77%	$5,226,305,913
1974	93%	1353	92%	78%	$3,392,563,311
1975	93%	1171	93%	79%	$2,896,529,196
1976	95%	1548	93%	79%	$3,776,242,327
1977	96%	2002	94%	80%	$4,815,580,759
1978	96%	2036	95%	81%	$4,828,716,333
1979	96%	1760	95%	82%	$4,115,764,198
1980	96%	1313	95%	82%	$3,027,870,258
1981	96%	1100	96%	83%	$2,501,972,257
1982	96%	1076	96%	83%	$2,405,535,892
1983	97%	1716	97%	84%	$3,791,241,327
1984	98%	1756	97%	84%	$3,838,979,077
1985	98%	1745	97%	85%	$3,767,638,708
TOTAL	73035				$152,426,647,358

6.8   References

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7   Conclusion

Through this study, it has been our goal to examine the relations between transportation and production. Motivated by 1) a suspicion that the relations between transportation and productivity change are stronger (deeper) than heretofore recognized 2) a desire to quantify off-system benefits of transportation development, 3) an observation of reduced productivity in residential construction (a large, important sector of the economy), and 4) the apparent inability of conventional analytical techniques to explain this reduction, we undertook this study of the relations between transportation services and the residential construction industry.

7.1   Summary

During the course of this study, we have examined the roles of transportation and Schumpeterian competition (innovation) in productivity change. To say that innovation (for that matter, production) could not have taken place without transportation is of no practical value; there are additional inputs requisite to innovation. What is relevant is the marginal contribution of transportation to changing production processes.

We have presented a methodology for examination of the contribution of transportation improvements to production. The method begins with identification of (housing) innovations, which Schumpeter called "the engine of productivity change." It then narrows to wallboard as representative of a class of innovations. Estimates of the benefit of the wallboard/drywall innovation were obtained by multiplying 1) the average savings attributable to adoption of the innovation (per house) by 2) the frequency of innovation applications (number of housing units utilizing the innovation).

The contributions of transportation improvements to production are conventionally calculated as savings due to reductions in input factor prices (on-system, such as reduced transportation costs). We have examined contributions at another level (off-system).

To estimate the off-system savings/gains facilitated by transportation, we need to know something about the way innovations are adopted. Besides directly contributing to production processes, transportation impacts the rate and saturation level for innovation

adoption. We may estimate this rate and saturation level for different transportation development scenarios. Alternative calculations of innovation benefits can therefore be obtained. Subtracting the alternative benefits from the observed gives an estimate of the benefits of transportation improvement to production (for the particular innovation). Using this approach, we estimated that the benefit for this single innovation is on the order of fourteen percent of truck related road costs.

7.2   Extensions

We have not obtained data to support extension of the benefit calculating methodology. However, the magnitude of the benefits shown for wallboard motivates initial extension of this work into housing innovations of a similar nature. The typology developed in Chapter 4 facilitates identification of similar innovations and classification of other housing innovations into manageable groups.

Additionally, more work needs to be done examining the relations between transportation and other sectors of production and consumption. Potentially appropriate candidates for this kind of analysis are high technology industry, agriculture, medicine, and recreation.

In general, the global concepts of economic long waves and product life cycles can be extended to services other than transportation. Particularly promising would be a similar study for the communications industry, for the modern world runs on flows of mass and information.

Extension of this type of off-system analysis into the areas mentioned above will be difficult, as data have not generally been recorded to suit this purpose. In addition, there are statistical confidentiality rules limiting data availability. The effort data required for comprehensive off-system analysis of other innovations, classes of innovations, industry and consumption sectors, and services of the economy can be extrapolated from the amount of effort in this study of a single innovation. However, the scale of such an effort should be compared to the tremendous amount of work of conventional on-system analysis.

7.3 Proposed Transportation Investments

During the last 20 years, the auto-highway system has been making the transition from exponential growth to full deployment. Problems that were simply "outgrown" during the rapid deployment years now present more difficult situations. In the current maturity phase, new approaches should be considered as the organization of production elements in society have changed since the design of today's transportation systems.

Much work is being done to improve on-system transportation performance. Chief issues are the cost of travel time, logistics, and maintenance of infrastructure. However, while the nation's transportation bill is large (by some accounts 20% of the GNP), trans-portation comprises only a small portion of production costs in most industries. Reduction of these costs, while worthwhile, provides no more than marginal reductions in the cost of goods and services.

Of greater importance to production is the enabling affect of transportation improvements. With the deployment of new transportation systems (canals, steam railroads, electric rail, automobile, truck, and air), opportunities for the reorganization of production (and subsequent reductions in the real cost of providing goods and services) have been presented.

Because we cannot predict specific changes in production technology that might be facilitated by improvements in transportation services, estimating benefits is difficult. By looking back at improvements enabled by past transportation development, one can begin to examine off-system benefits of future transportation improvements. In this study we have looked back.

Currently, a great deal of effort is being directed toward identification of the anticipated benefits and costs of automated highways, in-vehicle navigation, smart cars/streets, etc. Automated highways may promise a new transportation system, yet current efforts toward assessment of benefits are focused on direct impacts such as travel time savings and operating costs. Other new transportation technologies exhibit potential

and are being studied. These include both hard (maglev, vertical take-off and landing aircraft) and soft (logistics) technologies.

If technological problems can be worked out and, by evaluation of direct impacts, the cost of any of these proposed systems can be justified, decision makers may recommend implementation. Recall that the automobile found its first niche as a toy for the rich, and later, as a substitute for draft animals. Benefits were given as "requires less space, not as messy, and doesn't get tired." Larger impacts of the automobile were the reorganization of production, the city, and life in general. As with its predecessors, the next transportation system will facilitate reorganizations, the benefits and costs of which are not addressed by conventional analysis.

Our work has been toward recognizing reorganizations or transformations. It was the first of a large number of needed steps.

7.4   Housing Directions

Perhaps one way to identify desired transportation developments might be to examine "waiting-in-the-wings" sectoral opportunities. Promising housing innovations are prefabrication, ceramic building materials, and foam/concrete matrix technologies, innovations whose potential for productivity increases demand improved transportation services. For example, savings from prefabrication, resulting chiefly from reorganization and relocation of production, are constrained by transportation (USHUD, 1974). In Japan, prefabrication cost savings have been estimated at 10 percent for mass production economies alone and 30 percent for production economies associated with other innovations enabled by prefabrication (Kimura, 1985)[16]. There, the amount of

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[16]   Prefabrication allows: 1) engineering based designs implemented in the factory, (on-site construction methods make engineering based design cost prohibitive), 2) quality control and strict supervision of production, 3) precision manufacturing and mechanization of assembly lines using advanced robotics and machinery, 4) interchangeable parts used with standard designs (parts are obtained from a stockpile at the factory with no loss of work time waiting for shipments), 5) efficient use of new materials and methods (man-made materials - plastics, robotics, CAD/CAM, and environmental

transportation directly required by housing comprises one-third of total costs, yet productivity is higher than in the U.S. (where transportation accounts for about one-twentieth of total cost of residential construction). When other factors are involved (unit transportation costs are somewhat higher in Japan) conventional analysis would result in a lower marginal benefit of transportation for Japan.

Transportation costs are one constraint to the prefabrication of housing, and cost constraints can be addressed by conventional analytical techniques. However, there are transportation related constraints beyond costs. Size and weight restrictions inherent to current transportation systems constrain prefabrication innovation. In addition, there are production process innovations which are not feasible given the market sizes allowed by transportation systems.

Examination of transportation alternatives should include analysis of off-system as well as on-system impacts. For example, truck-only highways seem to exhibit potential for off-system benefit to the housing industry by enabling prefabrication benefits, benefits similar to those identified in this study and that could not be estimated by conventional techniques.

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test chambers), 6) reduction of cost uncertainties (with the system employed by Sekisui House of Japan, exact costs of CAD imaged homes are available immediately upon final design), 7) short construction times resulting in less insurance, losses due to weather, financing costs, and vandalism (mobile homes are typically manufactured in 1 to 3 days, modulars can be built in less than a month, and panelized construction takes less than half the time of conventional construction) 8) elimination of seasonality (in Sweden, indoor construction is economical in 90% of the housing industry), 9) reduced average materials costs (scale economies, reduction of waste), 10) reduced average labor cost (in 1983, 67 percent of manufactured housing costs went to materials, 15 percent to operating margins, and only 17 percent to labor; low skilled labor that can be retrained for various tasks on the job; increased worker productivity), and 11) reduced total cost (including all costs, the cost of manufactured housing is 10 to 30 percent lower than conventional housing, [Mathieu, 1986]; higher production levels are required for economic production of modular and panelized homes).

7.5   Closure

In the 1920's, an imperative to get rural America out of the mud led to the justification an extensive program of highway development. That development has had many other impacts, particularly on the organization of production. One of today's imperatives is congestion relief, and, as in the 1920's, the analysis of transportation alternatives is being based on meeting this imperative. However, as in the deployment of the highway system, transportation options will have off-system impacts. What society cannot afford are the lost opportunities resulting from non-investment in production improving transportation systems which fair poorly when judged on system performance criteria alone.

7.6   References

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