Relations Between Transportation and Production

William L. Garrison and Reginald R. Souleyrette II

Ways in which transportation improvements enhance production are investigated in this paper. The production of residential housing is used as a case in point. Several approaches to analysis are proposed. The one adopted emphasizes productivity improvements from technological change. After considering several ways that transportation services may relate to technological change, the authors provide an analysis of the diffusion of wallboard construction. Overall, the study concentrates on methodology and magnitudes. It provides a way of thinking about transportation and production relations, and indicates that service improvements may yield social savings of large magnitude.

The concern here is with the ways that transportation improvements enhance the uses of old resources and make new ones available, expand the scopes of markets and labor sheds, provide new production and consumption choices, and generally shape and improve social and economic aspects of life. To simplify, the word "production" is substituted for these transportation-related activities and the relations between transportation and production are analyzed.

The inquiry is unusual in two ways. First, the objective is to explore taken-for-granted relations in a crisp, analytic fashion. That is much easier said than done as this report on the work will indicate. Beginning with conventional analytical approaches, paths are explored through a maze. The path followed to its end related transportation services to innovation and innovation diffusion processes.

The inquiry is also unusual because its concern is with the ways that transportation services energize non-transportation activities. This is in contrast to today's situation in which transportation is mainly regarded as a necessary evil, and the evil is emphasized. It is evil because it gobbles energy, insults the environment, and takes money and time. In response, analyses, technologies, projects, and policies are developed to reduce costs and enhance safety, control environmental insults, and improve energy efficiency.

This study did not set out to quarrel with today's emphasis on costs and the consideration of externalities because such emphasis is always appropriate. It seeks to go beyond that emphasis to richer views of the necessity-demand side. We would like to fill in the blanks in statements such as, "Reduce costs or improve service quality in order to ____________." A slice of production, the construction of residential housing, is used as a case in point, which was eventually narrowed to the use of wallboard in housing construction. Although factual rather than fictitious, the housing production study should be read as a parable. It is intended to explore and illustrate principles.

The presentation begins by providing some information on the housing production industry. Next, several paths for formal analysis suggested by conventional analytical approaches are reviewed. However, examination of the data suggested formulating a new approach, and our formulation of a new approach is discussed in light of the data and the study's main objective. The analysis and findings follow. The closure reflects on the study. It suggests expanding existing principles to include transportation's role in innovation and productivity changes, comments on today's relations between transportation and production, and asks for a richer consideration of the needs for transportation improvements.

A simple statement of the conclusion is that in one small instance, transportation improvements enabled social savings measured in billions of dollars. That is part of our message, for it says that transportation improvements do consequential things for production. However, the larger part of the message has to do with methods. This is why the text to follow stresses the ways the problem was approached, how the analysis treated an instance from some larger set of relations, and the inferences derived from our results.

RESIDENTIAL HOUSING PRODUCTION

Housing production was selected as a case for study because it is an old, large, and ubiquitous activity. Housing is necessary for everyday life, and a housing problem is widely recognized. Housing production is transportation-intensive, and housing is produced using a complex of technologies. Dowall and Lynch refer to it as dispersed, diverse, discontinuous, and detached (*1*). Production is undertaken by many scattered firms of varied size, and the product and its environment vary (dispersed and diverse). It is a job-to-job business, sometimes seasonal (discontinuous). It uses contract labor and components produced away from the housing production sites (detached).

Modes of Production

In the United States, about 5 percent of residential construction uses modules. The modules are constructed at a factory, transported by truck, placed by crane, and assembled on-site. Somewhat similar is panelized construction, accounting for 12 to 22 percent of production. Panels for walls, floors, roofs,

W. L. Garrison, Institute of Transportation Studies, 112 McLaughlin Hall, University of California, Berkeley, Cal. 94720. R. R. Souleyrette II, Transportation Research Center, University of Nevada, Las Vegas, 4505 Maryland Parkway, Las Vegas, Nev. 89154.

and so on, are prepared in a factory and assembled on-site. More work is done on-site than is the case for modular construction. Manufactured or mobile home type construction accounts for about 12 to 22 percent of production. Site-built homes account for 51 to 74 percent of housing units. Classifications overlap because some prefabricated units are used in almost all construction. This and variations among classifications account for the ranges of percentages (*1,2*).

Speculation, or contract builders, produce one or a few units at a time. Larger production builders purchase large tracts of land, subdivide it, and produce the housing product. In all cases, specialized crews work on-site installing framing, plumbing, and so on. The amount of work done on-site varies by mode of production, of course.

As the sketch suggests, there is considerable variability in production ranging from near-complete on-site to near-complete off-site. The timing and place of material and labor inputs vary accordingly. On average, off-site employment of labor in construction is about 13 percent of on-site labor employment, and labor required to install manufactured products comprises about 90 percent of on-site employment (*1,3*).

In Trouble

It is widely agreed that productivity gains are nil, if not negative, in housing production and construction in general. There is agreement despite the difficulty of measuring productivity and productivity changes in these activities. The industry is diverse, and data collection is difficult. Housing is not a highly standardized product. There are regional and other differences in the product and its inputs at any time. The housing product has changed over the years.

It appears that productivity gains occurred from about the end of World War II to the late 1960s, and declined subsequently. One source reports construction productivity improvements of 3.4 percent per year between 1948 and 1965 with a decline of 1.8 percent per year thereafter (*4*). Another source reporting on housing estimated an increase of 2.4 percent per year from 1950 through 1968 and a decline of 2.8 percent per year from 1969 through 1978 (*5*). In both cases, the rate declined 5.2 percent per year. Similar trends in highway construction productivity are well known to the transportation community.

The structure of housing production yields limited research and development, difficulties of transferring technology, and a varied market for products and processes. These are cited as the main causes for the productivity problem. Increases in land, energy, and capital costs, and the loss of economy of scale are also cited as causes. Declining productivity adversely affects real costs and housing prices. Beyond that, the decline adversely affects improving living standards and real economic growth.

Interestingly, transportation services are seen as a minor part of the housing productivity problem. Services get minor mention when manufactured housing is discussed, and if services appear at all in other discussions, they are far down laundry lists of problems. Yet reflecting on past changes in the industry, it is clear that transportation improvements had much to do with the availability of materials and with the mobility so important to the assignment of tools and specialized labor to on-site tasks. The past is out-of-sight and out-of-mind.

TRANSPORTATION AND HOUSING

As the brief sketch suggests, housing production provides rich topics for the transportation analyst. Working from existing principles and conventional methods of analysis, three approaches to topics will now be discussed: investigating relations between transportation and land for housing, the housing production system, and the producer's choice of production mode. Although these approaches were not followed in this work, it is important to say why they were not. Also, our approach was complementary, and future work combining approaches might be fruitful.

General principles have been stated here and there. For instance, Adam Smith pointed out in 1776 that transportation improvements yield increased specialization and associated efficiencies (*6*). Based on an extensive review, Ringwalt's 1888 study yielded 14 conclusions about transportation in the United States (*7*). His conclusions took the form: "Where ever a railroad goes, . . . " There is also DuPuit's insight of 1844: "The ultimate aim of a means of communication must be to reduce not the costs of transport, but the costs of production" (*8*). Although statements are available, there apparently is no systematic list of principles that might provide a starting point for this work, so the authors proceeded by stating problems for analysis and imagining principles that might be appropriate.

Land Use Relations

There is the well-known relation between land rents and transportation services; the relation ties transportation services to the supply and value of land at different locations. Land costs are, say, 15 to 25 percent of housing production costs, so matching transportation and land supply to housing markets is an important matter.

The interpretation of changes in location rents as a measure of something transportation does that is worth doing has been of long-standing interest to transportation professionals. The 1956 Interstate legislation calling for a cost allocation study asked that there be investigations of the user (on-system) and nonuser (off-system) benefits of highway investment. That call yielded studies of user cost savings and studies of nonuser benefits, the latter under the rubric of highway impacts on land development. But even at that time, the impact studies and the conjecture that funding might be tied to impacts were hardly new. They date at least from George Stevenson's 1856 remarks on the development of the London-Birmingham railroad and the 1790 funding scheme of George Washington and Thomas Jefferson for the development of Washington, D.C. (*9,10*).

Today, attention to the relation has reemerged under the rubric of value capture. Land owners whose property values are enhanced by improved transportation services are expected to contribute to facility investment costs. That was not the result of the 1956 study. It ignored nonuser benefits and emphasized user costs and the impact of vehicles of different types on facility costs.

The impact studies triggered by the cost allocation study triggered, in turn, reexamination of the theory of location rents. That theory leaves no room for nonuser benefits as something apart from user benefits: nonuser benefits appear as consumers' surplus created by transportation improvements (*11*). The modern debate, to the extent there is debate, may be no more than a debate about who gets the surplus.

Even so, this study began with the thought that there was more to the principle of nonuser benefits; that although user (on-system) benefits overlapped with nonuser (off-system) benefits, distinctive nonuser benefits existed that ought to be recognized in theory and practice. A close investigation of well-known principles would clarify the situation, principles such as these: transportation makes land available for housing; it offers opportunities for labor, tool, and product specialization; and it enables the movement of products for final assembly at the construction site.

Production and Economy of Space

There is no choice about where the final housing product will be produced; it is produced at the market. But as the brief discussion of housing production noted, a range of spatial production modes exists. Toward one extreme, the mobile home, almost all production is done off-site. On-site production is toward another extreme. These "toward-extremes" production formats are realizations from a tree-like production pattern. As noted, off-site processing may yield modules, finished units, or prefabricated components. On-site production largely skips these production paths, although there is much preprocessing off-site.

To what extent can analysis using the principles be investigated in the frame of the spatial structure of production? An approach based on concepts from spatial economics, regional science, and geography seems appropriate. The production space is endowed with markets and resources. With the usual assumptions, production location and output decisions interacting with resources and markets yield an optimal production pattern. The analytic task is to specify the production system in an equation system and investigate how transportation services affect the system.

Choice of Production Mode

As mentioned, the housing producer may choose among production modes—use of modules, panelized construction, and so on. Once the first choice of production mode is made, choices follow of a make-or-buy character (e.g., subcontract foundation work or not), choices among products to be installed, and choices among and about the specialized labor to be used. A choice analysis is suggested, a nested choice analysis of the type used in transportation mode choice analysis.

Choices are made among products and inputs, and in model specification it seems important to include space and time considerations because the production requires significant amounts of space and time, and these parameters may bear on choices made. Transportation services might bear on space-accessibility and enter in a logistics-time way, in addition to direct relations to available inputs.

FIRST EMPIRICAL INVESTIGATIONS

Having identified approaches to analysis, exploration began on the history of housing production and data sets that might be brought to formal system specifications. Two results were expected. First, production is complicated by the many paths and products in the production stream, and, second, there are sharp limitations on data availability. These expected results were to be dealt with through in-depth exploration of fragments of information.

Unexpected Information

Although the fragments of information were explored, the ambitious plan to treat the system as a whole was set aside when the data began to suggest relations that did not fit the process specifications very well. It is not practicable to reproduce the mass of data here, so examples of unexpected results will be given. (Occasionally data were found specific to residential construction; most available data are for construction of all types.)

Examining the labor inputs to production revealed a number of trends similar to those shown in Figures 1 and 2. [The

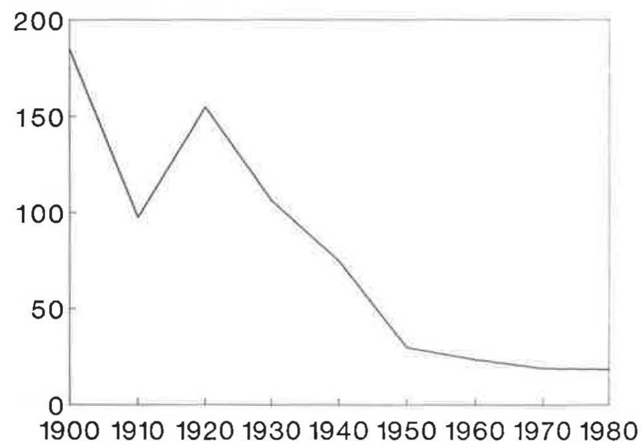


FIGURE 1 Carpenters per million 1967 dollars building value.

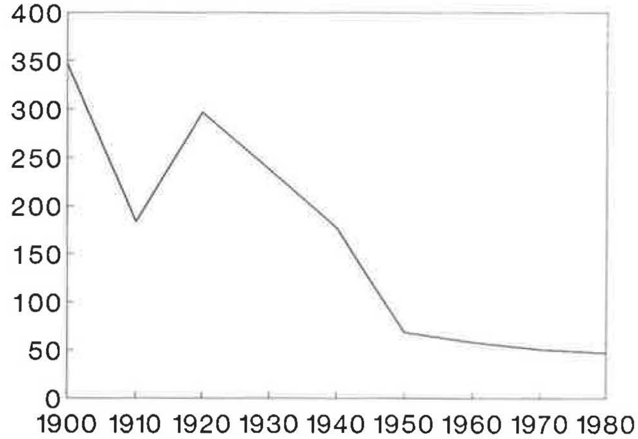


FIGURE 2 Total workers in six specialized trades (per million 1967 dollars building value).

curves shown in Figures 1–5 were calculated from Census Bureau data (*12,13*).] It was expected that the use of automobiles and small trucks to move labor to and among construction sites would improve the efficiency of labor inputs. Indeed, a 1921 report on the advantages of motor vehicle use stated that contractors' use of vehicles increased productivity by 51 percent (*14*). But that is much less than the almost order-of-magnitude improvement suggested by the figures.

Figures 3 and 4 display another unexpected result. Transportation improves access to resources and increases competition, so lower materials prices were expected. However, the figures display a long term increase in real prices, with variations around a set point since about 1950. Again, these data are fragments from a larger set.

Explaining the Unexpected

One option for dealing with these unexpected results was to return to the process specifications and begin to introduce plausible factors that might have yielded the findings. In the case of materials, for instance, one might suppose that real income increases, working with demand for improved quality, might have interacted with transportation's provision of increased access to products to yield increasing materials costs.

But two considerations pressed for another option. The first was the symmetry between realizations of transportation services and realizations of housing's production input processes. Examining truck service, for instance, suggests a rough correlation between the period of its rapid deployment and changes in inputs to housing construction. (Compare Figure 5 with previous figures.) In addition to such aggregate relations, bits and pieces of fragmentary data link the realizations. For instance, the development of canals enabled the marketing of building stone far from quarries, with labor at the quarry providing for stone finishing. This process ran as canals were deployed, and its realization must have tapered as the canals tended to full deployment. Housing producers shifted to a more expensive, higher quality product. Preprocessed, the product reduced demand for on-site labor. Though not discussed here, many similar relationships appeared for the rail, water, and highway modes.

Consideration of forces prevailing during the period that the transportation and housing development processes have been at work also pressed for an alternative approach. This was a period of great technological change. Capturing those changes in the process specifications considered in the previous section of this paper would require an exhaustive inventory of past and present processes. Models would need to be constructed to incorporate choices of one process or another and one production place or another. At first approximation, that is a vast task. Suppose, for instance, 50 processes in the production stream might take place in 50 places. This yields 50^{50} possible arrangements of processes. That number is an upper bound because processes are interdependent; some feed to others.

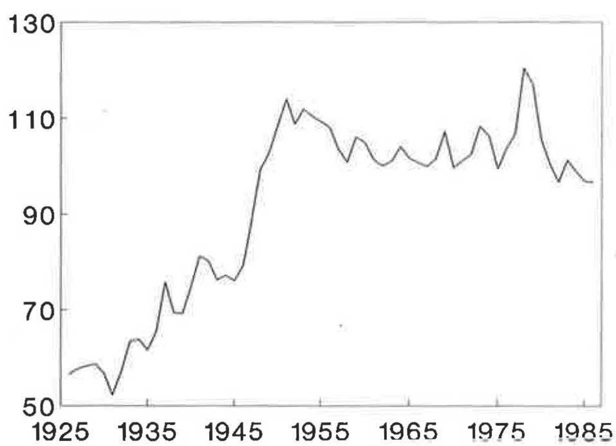


FIGURE 3 Real price of millwork (index: 1967 = 100).

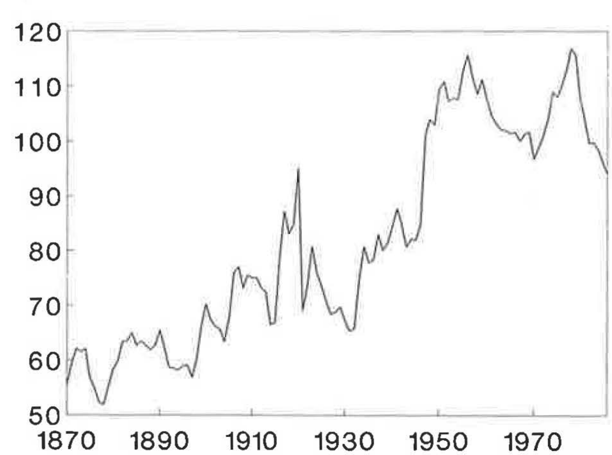


FIGURE 4 Real price of construction materials (index: 1967 = 100).

TRANSPORTATION AND TECHNOLOGICAL CHANGE IN HOUSING PRODUCTION

An investigation of the evolution of housing production technology was made to explore how technological change might enter the analysis.

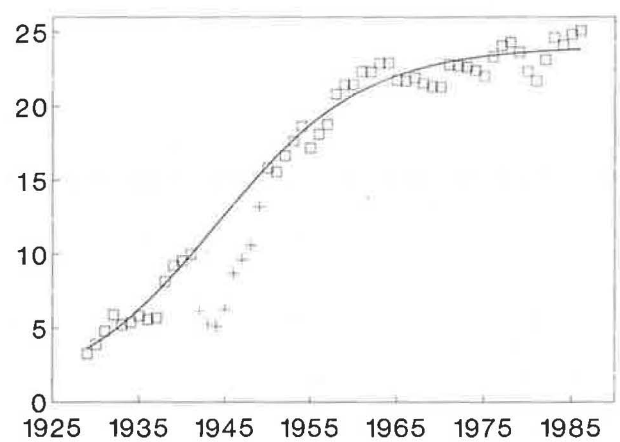


FIGURE 5 Motor truck freight as a percent of all intercity freight.

Inventory and Classification

Assuming that useful insights about transportation-housing production technologies would emerge from examining examples, the housing technology investigation began with an inventory of housing innovations. About 225 innovations were identified, beginning with the transition from earth- to sill-mounted footings about year 1200 and ending with today's interest in robotics. As would be expected, the completeness of the list was not known, and entries were variable in type and importance. Some technologies were clearly derivative of earlier ones; double counting was a problem.

Attempting to make the list usable, classifications were imposed. First, entries were arrayed on a time line. As mentioned, some technologies are derivative of others. This was found to be the case, and transportation relations entered in mixed ways. For instance, wallpaper became popular in the early 1700s, a development turning on fashion trends and the innovation of printing with transportation making the product available. The development of the Howe truss about 1840 followed earlier developments of truss framing and knowledge of the behavior of structures. The need for transportation structures no doubt played a role in its innovation.

A time line was also used because the authors were curious about the presence of innovation bursts and their relations to transportation and long wave theory. Invention is a continuous process, but invention-based innovations occur in temporal bursts (*15*). In turn, these bursts are related to long waves in the economy (*16*). One explanation for the relation is that economic down-cycles and depressions create opportunities for innovations. The resulting burst of innovations, followed by demand for new products and increased employment and investment opportunities, then drives an up-cycle in the economy. The empirical and theoretical underpinnings of long wave theory are much debated; transportation innovation and deployment have no special place in the debate. A line of inquiry was suggested, but not pursued. Even so, it was briefly mentioned because the concepts are discussed again later in this paper.

A second classification was attempted, one on process-versus-product technologies with an effort to scale transportation intensiveness within those categories. This effort was not very successful. Some technologies could not be neatly assigned to the process or product categories. The question of transportation intensiveness was fuzzy; an example illustrates the problem. The powered-nail gun is a product, yet it is a product for use in the construction process. It is easy to transport, so at first glance, assign it to a not-transportation-intensive category. But on second thought, that assignment is not so neat. Surely the development and marketing of a specialized product of this type turns on transportation access to a large market. Its efficient use at a site is tied to transport and use of labor. The ability to move the gun from site to site also makes for its efficient use.

Processes of Innovation

Problems encountered in striving to develop useful classifications turned attention to considerations of processes of innovation and diffusion. The classic view of the innovation process has a design flair: building blocks are arrayed in a new design. Stevenson's first railroad, for example, combined physical building blocks from tramways and steam engines with canal and road common carrier concepts and franchise and financing concepts from public works generally. In a sense, the building blocks are clay, and they are molded into bricks (*17*).

That classic view applies in a straightforward way to the transportation modes (*18,19*). Extending it to products transported for use in housing production is one option; that is, think of transportation services as a building block for products, a transportability building block. This may be reflected in the size and weight characteristics of a product, in a companion packaging innovation, or in the product design. A product, such as an automatic washing machine, is built to survive the forces acting on it as it is used and when it is shipped. How do improved transportation services result in product innovations and improvements?

It has been pointed out that railroads were the first of the large modern businesses, and many railroad innovations were adopted in subsequent business developments. Railroad organization, corporate control, and uses of information have received particular attention (*20*). The subject is much broader, however. The development of transportation spawned generic public utility law; product testing, standards, and certification procedures; large scale financial markets; governments' roles in safety and labor affairs; accounting procedures; and many other things. All such innovations threaded their way through the economy. So another question that may be posed relates to the ways transportation innovations have been shaped and used in non-transportation sectors.

Finally, transportation (and communications) plays a role in the diffusion of innovations. Many innovations are embodied in products, and innovations are diffused as products are transported. Considering diffusion and the ways transportation may relate to the forms of products or services, one may think of transportation innovation as a companion innovation to innovations in other sectors. Transportation works with other sectors to provide new ways of doing things.

WALLBOARD

To move from generalizations to data-based analysis of the relations among transportation, innovation, and productivity gains, a case study was conducted of the substitution of wallboard for lath and plaster.

Wallboard (gypsum plaster board or drywall) was patented in 1895 and began to substitute for lath and plaster interior wall construction in the 1920s. Its installed cost is approximately one-eighth the cost of lath and plaster, and its cost comprises 5 to 15 percent of the cost of residential construction, depending on the type of housing. Wallboard is one of several products, such as millwork, fabricated off-site for installation on-site. Relative to lath and plaster, its installation is rapid and uses low cost labor.

Transportation relations bear in many ways. The patterns of gypsum mining, processing plants, and distribution are transportation dependent and have shifted as transportation services have changed. Today's product is a sheet of plaster covered with paper; it is sized 4 × 8 or 4 × 12 ft. The product is larger than it was in earlier days, and its strength, covering, and size appear to have responded to the transportation services available.

Process Specification

It was mentioned that transportation development might affect innovations in other sectors. Other sectors might emulate transportation innovations, configure products or services to the nature of the transportation services available, and/or use transportation to aid innovation diffusion. The innovation of wallboard appears to be affected in these ways. However, the emphasis in the analysis to follow is limited to the role of truck freight service in the diffusion of the wallboard innovation. This is a partial investigation of the ways transportation serves as a companion innovation to innovations in other sectors. A conservative, straightforward analysis was sought, one that could be compared with Robert Fogel's analysis of the contribution of railroads to economic growth (*21*).

Fogel posed the counterfactual hypothesis that river and canal services developed in the absence of railroad development. He then undertook a detailed geographical analysis to compare the cost of transportation by water-based services (fed by animal-drawn vehicles) with the cost of rail transportation. He concluded that railroads made only a minor difference although water service cost was slightly higher than rail cost, some areas could not be easily served, and seasonal flow disruptions on canals and rivers were bothersome. American economic development would have been much the same without the aid of railroads.

Fogel's emphasis was on settlement and agriculture, and his terms of reference and careful analysis leave little room for quarrel. However, great technological change occurred during the period Fogel studied. As Beniger pointed out, the railroad (and the telegraph) enabled continuous flow, large scale production, and the creation of large efficient industries (*22*). Basalla's discussion of the slow invasion of the market by the McCormick reaper points out that its wide adoption waited on railroad-based settlement (*23*).

The following analysis proceeds in the style of Fogel. That is, the counterfactual hypothesis is posed that truck-highway service did not develop; shipment of wallboard was by rail and animal-drawn vehicles. With the McCormick reaper case in mind, it is assumed that the productivity gain from the use of wallboard would have pulled its eventual adoption. The question, then, is, What is the difference between the speed and degree of the achievement of wallboard-derived productivity gains with and without truck service?

Market Penetration Analysis

To explore innovation diffusion rates and degrees of market saturation, a technology substitution analysis was made: How did wallboard substitute for lath and plaster construction? One estimate of social savings was made. To indicate how the quantity of social savings might change if assumptions used in the analysis were changed, the sensitivity of the result to model parameters was explored.

The Fisher-Pry model, a three-parameter logistics equation, was chosen for application (*24*). The functional form of the model is:

$$X(t) = \frac{K}{1 + \exp(-\alpha t - \beta)} \qquad (1)$$

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 wallboard),
α = a parameter controlling the rate of growth, and
β = a parameter positioning the function in time.

Although the physical interpretations for the parameters given above are clear, the values for α and β are not intuitively apparent. To facilitate specification of parameter ranges, a transformation used by Nakicenovic was applied to the parameters (*25*).

Because the logistic function is symmetrical, the maximum rate of growth occurs at the inflection point, t_{50}, where the value of the function reaches half the saturation value, ($X = 0.5 \cdot K$). Substituting into Equation 1 and solving for t gives $t_{50} = -\beta/\alpha$. Next, a growth rate, δ_t, is 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 $X = 0.9 \cdot K$) and t_{10}(t at $X = 0.1 \cdot K$) yields $\delta_t = (\ln 81)/\alpha = 4.394/\alpha$. In terms of these more intuitive redefined parameters, the original parameters can be derived:

$$\alpha = 4.394/\delta_t \qquad \beta = \frac{4.394 \cdot t_{50}}{\delta_t} \qquad (2)$$

The equation may be normalized by setting $X(t)/K = f(t)$. This reduces the number of parameters to two if K is known. For the wallboard case, there has been simple substitution of one commodity (wallboard) for another (lath and plaster). The saturation value K is the size of the market (1.00), 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. To measure the magnitude of plaster and lath construction, figures for the production of building plaster were tabulated (*26*). 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 (*27*). Although wallboard does not directly substitute for all these plaster applications, those 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 presents data for production of plaster and wallboard from 1921 to 1985 in tons per building value. [The curves shown in Figures 6–8 were calculated from data obtained elsewhere (26).] Output was normalized to building value because of the wide variation in building volume over the time of interest. Although measures more appropriate for comparison of the two products may be specified (e.g., square feet of wall/ceiling covered or number of homes built using

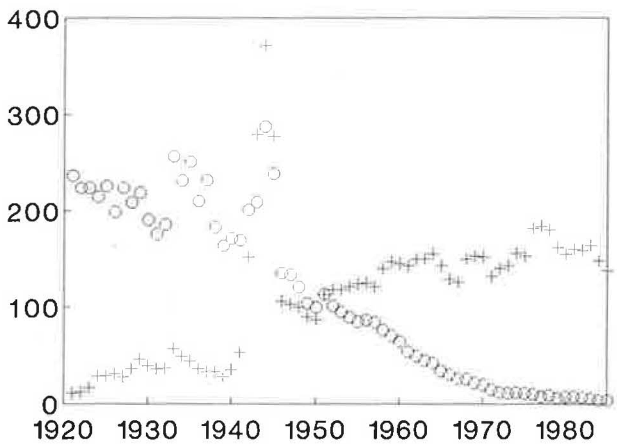


FIGURE 6 plaster (o) versus wallboard (+) production (tons per million 1967 dollars building value).

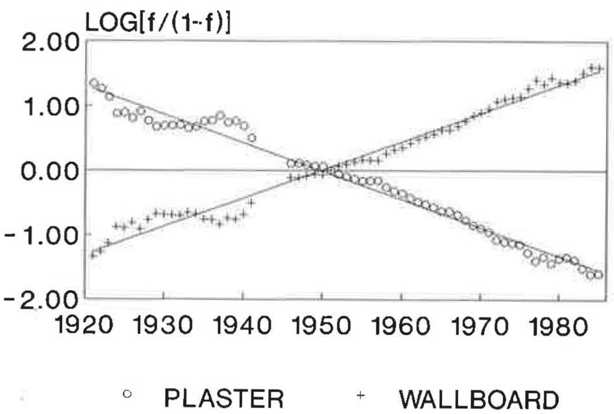


FIGURE 7 Substitution of wallboard for plaster (by weight).

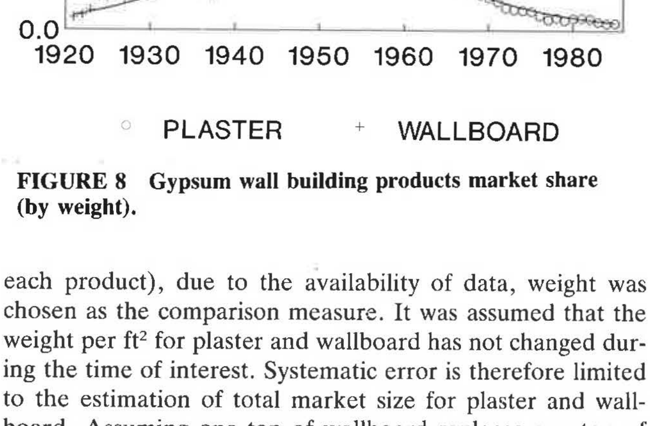


FIGURE 8 Gypsum wall building products market share (by weight).

each product), due to the availability of data, weight was chosen as the comparison measure. It was assumed that the weight per ft^2 for plaster and wallboard has not changed during the time of interest. Systematic error is therefore limited to the estimation of total market size for plaster and wallboard. Assuming one ton of wallboard replaces one ton of plaster, market shares may be computed.

Using ordinary least squares, the parameters of the logistic substitution model were estimated. The data were normalized by setting $f(t) = X(t)/K$. By the time of this study, wallboard had captured essentially 100 percent of the interior wall finishing market, therefore the value used for saturation value, K, was 1.00. Resulting parameters were calculated as: t_{50} = 1950 (time at 50 percent substitution = $\beta \cdot \delta_t / 4.394$) and δ_t = 43 years (time between 10 and 90 percent wallboard substitution = $4.394/\alpha$). (See Figure 7; data for 1942–1945 were not used in the regressions because the relative production of plaster and plaster products seems to have responded to World War II needs for temporary buildings.)

Wallboard construction took 33 years to penetrate 10 percent of the plaster and lath market (1895–1928). The substitution of wallboard for plaster and lath then proceeded at a rapid pace, reaching 50 percent in an 22 additional years (in 1950). Wallboard had attained 90 percent market saturation by 1972.

A graphical interpretation of the analysis presented above is given in Figure 8 showing market shares for plaster and wallboard (actual and estimated by the model).

Estimate of Social Savings

Three parameters control the curve used to approximate the substitution of wallboard for plaster and lath construction. These parameters affect the rate (δ_t), the placement in time (t_{50}), and saturation value (K) of the substitution process. Social savings are calculated as the difference between the actual substitution curve (best fit) and a curve for a hypothetical case assuming the truck-highway system had not been deployed. While the exact shape of the hypothetical curve is uncertain, some conservative estimates can be made for its parameters.

Over the last 70 years or so, wallboard substituted for plaster. Because wallboard and plaster/lath are relatively direct substitutes, construction cost savings can be taken as the motivation for substitution. So, it is appropriate to estimate the savings represented by the adoption of wallboard in the average house. The cost of wallboard represents about 5 percent of the cost of the average new house. Plaster and lath costs about eight times as much. Assuming that the average new house costs $50,000 (constant 1989 dollars, conservatively low), the savings are calculated to be $17,500. (Elasticity is ignored; the demand for higher-priced, plastered homes would be less than for lower-priced, wallboard homes.)

As noted, substitution of drywall for plaster would have taken place even without the deployment of the truck-highway system. It is assumed only that had the truck-highway system not been deployed, the substitution of drywall for plaster would have proceeded less rapidly (δ_t = 50 years instead of 43 years), a few years later (t_{50} = 1955 rather than 1950), and to a saturation value of less than 100 percent (90 percent).

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

$$X(t) \cdot \$17{,}500 \cdot U \quad (3)$$

where U is the number of housing units produced that year, and $X(t)$ is the market penetration for either the actual or hypothetical case. Summing these savings from the early years of substitution to the present for both cases and computing the difference gives the portion of social savings provided by the drywall innovation attributable to truck-highway service.

Based on the hypothetical case parameters, it is calculated that the 1985 value of the social savings attributable to trucks for just this one housing innovation are $4.1 billion, and the savings since 1921 are $181 billion. (For comparison, $4.1 billion is about 1.3 percent of the nation's annual freight transportation expenditures.)

Figure 9 shows the actual substitution of drywall for plaster, the best fit technological substitution curve, and the curve demonstrating the substitution rate for the hypothetical no-truck deployment case.

Critique of the Analysis

The sensitivity of the results to the numerical assumptions may be easily stated. The magnitude of the savings is most sensitive to changes in the parameter t_{50}, time at 50 percent market saturation. For each change of one year in t_{50}, the savings change by $16.5 billion or 9.1 percent of the total (Figure 10). The calculations used 1955 as the 50 percent market saturation without truck service, compared to 1950 with truck service. That lag is regarded as reasonable because of the 30 years it took for the wallboard innovation to achieve 10 percent market penetration and, especially, because the period of slow market penetration corresponds to the beginnings of truck service, as shown in Figure 5.

Of next greatest sensitivity is the parameter K. Each 1 percent drop in the saturation level, K, results in nearly $7.5 billion (4.1 percent) in additional cumulative savings (Figure 11). The savings are least sensitive to the parameter δ_ν, time between 10 and 90 percent substitution. Each year's increase in δ_t results in only about $1.5 billion (0.8 percent) in total savings (Figure 12).

A broad critique of the analysis is also straightforward. Several ways transportation might interrelate with innovation processes were stated. Seeking a conservative, simple analysis, only one of these interrelations was investigated: the role of transportation in innovation diffusion. This limited analysis does not fully examine wallboard as a companion innovation to truck services. It also does not consider how modern transportation enables the continuous flow wallboard production process.

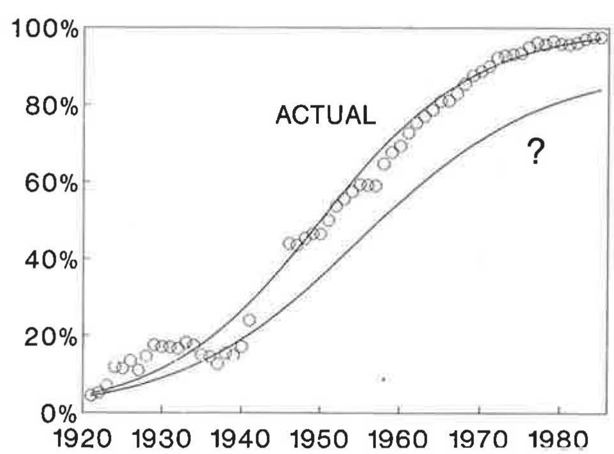
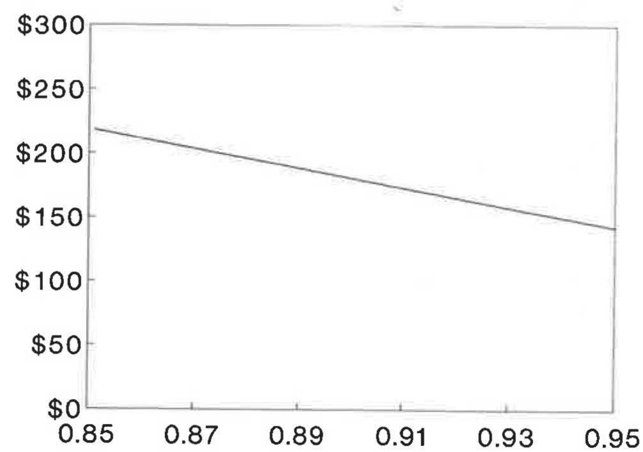


FIGURE 9 Wallboard market penetration.



penetration).

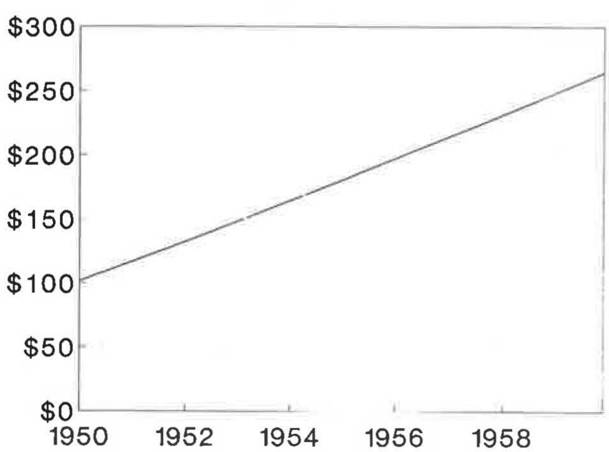


FIGURE 10 Sensitivity of savings to t_{50} (time at 50 percent market penetration).

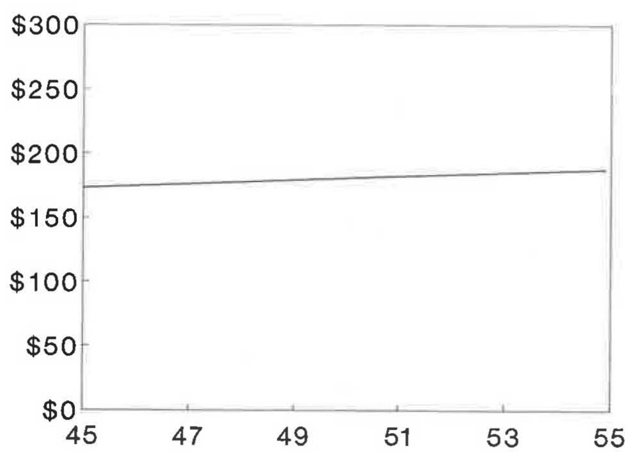


FIGURE 12 Sensitivity of savings to δ_t (Time required for market penetration).

There are many arguable details of the analysis. For instance, housing producers' options were not limited to wallboard versus plaster because wood planks were available and used to cover interior walls. It was not known how rail and collector/distributor services might have evolved absent truck services. Only an estimate is available of today's difference between the costs of installing plaster and wallboard; yesterday's costs might differ. Many other points can be made.

The many options for critique say that the estimate of social savings is very rough; it is a "ballpark" figure. The estimate of social savings might have been greater if the analysis extended beyond the diffusion process. The estimate might have been greater or less if better information was available on the rate of diffusion and the extent of market penetration absent truck services and if details of the substitution process had been included in the analysis. But even with these possibilities, the estimate points to a sizable relation; that is the important finding from the analysis.

REFLECTIONS

This section makes much use of such words as "perhaps" and "might" as it reflects on the study and strives for inferences.

The introduction emphasized general statements or principles illuminating the "what transportation does that is worth doing" question; it stated that principles were being sought. As currently stated, perhaps the operative word describing principles is "organization." Improved services yield more efficient organizations; for instance, this resource is from here rather than there. Persons seeking employment can organize the search for employment differently, or customers can skip the corner store to shop for a greater variety of products in a large shopping center. Such changes as these are welcome because progress is made through better organization.

But innovation is a major engine of progress, and perhaps a beginning has been achieved on principles that link service improvements to innovations. Perhaps the usual list of principles, such as the "bringing new resources to the economy" principle, ought to be followed by sentences of this sort: "In doing these things, transportation improvements permit doing old things in new ways, the diffusion of improved technologies, and the carrying out of new combinations producing new products. It is in these ways that transportation improvements mainly contribute to economic and social progress."

The "mainly" in the second of the two statements is quite strong, and is meant to be. Transportation interacting with the wallboard innovation made a sizable contribution to housing productivity, and it seems likely that many other such contributions could be found in housing and other endeavors. Our "carrying out of new combinations" in the first sentence is from Schumpeter, and the second sentence responds to the increasing recognition of the role of innovation and technological change in progress, Schumpeter's thesis (*28–31*). Existing principles stress improved organizations for existing activities, but new combinations are a larger force for progress.

The discussion mentioned innovation waves and the hypothesis that innovation waves are linked to long waves in the economy. Andersson has proposed that transportation technological revolutions occasion sharp increases in production (*32*). He suggests we would do well to think of the commercial and industrial revolutions as transportation revolutions. That seems proper from the timing of developments, and perhaps the linking mechanism is transportation's role in providing opportunities for innovation and innovation diffusion. Perhaps, too, transportation revolutions drive or are driven by long waves of economic development.

If transportation is instrumental in technological development and diffusion, as is suggested here, the present situation in transportation is extremely troublesome. It is even more troublesome if transportation drives long waves in the economy, as the discussion above suggests. Transportation systems have well-defined technological structures, and many are well deployed in the more developed nations. Should the inference be drawn that the maturity of transportation systems is limiting progress? Some inquiry might help define the extent to which that is true. Perhaps one would find that limiting-by-conditioning is the situation. Society runs on flows of mass and information, and the recipes for organizing and controlling flows are complex. At a time when information flow opportunities are increasing sharply, transportation's stagnation may be limiting and conditioning opportunities.

As it proceeded, this discussion considered a number of directions for inquiry and steered along an ever-narrowing path. Paths not followed were not rejected, just not followed. Following them might be fruitful. It might be useful, for instance, to respecify the land relation to recognize that transportation services may permit new combinations of uses of land. It might be useful to examine some cases in which transportation is an explicit building block for innovations, the offshore drilling platform is an example, because how it is to be transported and erected at the site bears on what can be done. In undertaking investigations, of course, one must avoid claiming too much. That there would be little social and economic development without transportation is not the issue, because such statements can be made about many things. It is the marginal improvements in service that must be judged.

With respect to housing, figures were presented showing a rough correlation between the deployment of transportation and improvements in the housing production process. Surely the relationship is not accidental. The parallel between today's situations in housing and transportation also may not be accidental: housing production productivity gains are nil or negative; land transportation is technologically mature and facilities are largely deployed; and productivity gains are nil or negative (*33*). This observation suggests that today's housing problems are incompletely stated. Transportation has not offered opportunities recently, so it is out-of-mind. But perhaps it ought to be put on problem lists and a good part of today's housing problem recognized as a transportation problem. Perhaps there are other sectors whose problems are transportation problems? Again, the modern world runs on flows of mass and information, and one might suspect that transportation problems are broad indeed. It was noted in the introduction that cost reductions or service enhancements steer transportation investments. One can not quarrel with that because efficiency is always desirable. Even so, there may be a problem.

It is understandable that the calculi of cost reduction or service improvements are applied to the traffic that can be seen and measured, and this focuses investments on the transportation uses of existing activities. There are few or no signals for investments that might enhance doing old things in new ways or doing new things. So perhaps there is an unfortunate bias in investment programs; they preserve the old through ever-decreasing marginal improvements rather than enhance the new. Put another way, they enhance only one route for progress—greater efficiency of existing activities—and ignore innovation as the major route for progress.

More incisive work on the demand for transportation seems merited. In theory, that could be done through increased attention to elasticity of demand, because such attention would flag new developments clamoring for service. But without some sense of the origins of new developments, such work would have a fishing-expedition character. So perhaps work on the demand for transportation should begin with innovation considerations, and perhaps policy should give greater emphasis to new transportation services rather than enhanced old services. In part, work might be done by paying close attention to and giving weight to new things creating new demands. It might also pay closer attention to general principles incorporating innovation considerations, and give weight to investments that enhance innovation possibilities.

These suggestions are easy to make, but difficult to implement. The vision of a link between transportation services, innovation, and productivity gains through the economy is not widely held, and the literature of innovation overlooks transportation (e.g., *34, 35*). The situation is understandable: relations are complex and the relative maturity of transportation systems places them out-of-view.

Perhaps improved transportation services had their major impacts yesterday, and today's marginal improvements are rather irrelevant. How to energize transportation development in a way that energizes production relations is, perhaps, a large part of today's transportation problem.

ACKNOWLEDGMENT

This research was supported by the Institute of Transportation Studies and the Transportation Center at Berkeley (*36*).

REFERENCES

1. D. E. Dowall and J. Lynch. *The Impacts of Technological Change on Residential Construction: A Case Study of the United States Manufactured Housing Industry*. Working Paper 449, Institute of Urban and Regional Development, University of California, Berkeley, Calif., 1986.
2. R. Mathieu. The Prefabricated Housing Industries in the United States, Sweden, and Japan. *Construction Review*. July–Aug. 1987, pp. 2–21.
3. R. Ball and L. Ludwig. Labor Requirements for Construction of Single Family Houses. *Monthly Labor Review*. Dec. 1971, pp. 12–14.
4. *Construction*. Center for Construction and Education, Massachusetts Institute of Technology, Cambridge, Mass., 1988.
5. K. H. Stokes, Jr. An Examination of the Productivity Decline in the Construction Industry. *The Review of Economics and Statistics*, 1981, pp. 495–502.
6. A. Smith. *The Wealth of Nations*. The University of Chicago Press, Chicago, Ill., 1976 ed.
7. L. J. Ringwalt. *Development of Transportation Systems in the United States*. World Railway Office, Philadelphia, Pa., 1888.
8. J. DuPuit. On the Measurement of the Utility of Public Works. Translated by R. H. Barback and republished in *Economic Papers*. 1952, pp. 83–110.
9. G. Stevenson. Resumé of the Railroad System. Republished in Samuel Smiles, The *Life of George Stevenson*. Tickor and Fields, Boston, Mass., 1858.
10. A. E. Cowdrey. *A City for the Nation: The Army Engineers and the Building of Washington, D.C.* Historic Division, Office of the Chief of Engineers, Washington, D.C., 1978.
11. H. Mohring. *Transportation Economics*. Ballinger Publishing Company, Cambridge, Mass., 1976.
12. U. S. Department of Commerce. *Historical Statistics of the United States*. Bureau of the Census, Washington, D.C., 1975.
13. U. S. Department of Commerce. *Statistical Abstract of the United States*. Bureau of the Census, Washington, D.C., various editions, 1971–1988.
14. National Automobile Chamber of Commerce. *Facts and Figures of the Automobile Industry*. New York, N.Y., 1921.
15. N. Kondratieff. *The Long Wave Cycle*. New York, N.Y., 1984.
16. G. O. Mensch. *Stalemate in Technology: Innovations Overcome the Depression*. Ballinger Publishing Company, Cambridge, Mass., 1979.
17. D. Sahal. *Patterns of Technological Innovation*. Reading, Mass., Addison-Wesley, 1981.
18. W. L. Garrison. *Transportation Technology: Yesterday's Accomplishments, Today's Opportunities*. New Zealand Roading Symposium, 1987, pp. 865–877.
19. W. L. Garrison. Technology Development: Introduction. *Transportation Research*. 1984, pp. 267–276.
20. A. D. Chandler and S. Salsbury. The Railroads: Innovators in Modern Business Administration. In E. Mazlish, ed., *The Railroad and the Space Program*. MIT Press, Cambridge, Mass., 1965.
21. R. J. Fogel. *Railroads and American Economic Growth*. Johns Hopkins University Press, Baltimore, Md., 1964.
22. J. R. Beniger. *The Control Revolution: Technological and Economic Origins of the Information Society*. Cambridge, Mass., Harvard University Press, 1986.
23. G. Basalla. *The Evolution of Technology*. New York, N.Y., Cambridge University Press, 1988.
24. J. C. Fisher and R. H. Pry. A Simple Substitution Model of Technological Change. *Technological Forecasting and Social Change*. 1971, pp. 75–88.
25. N. Nakicenovic. Dynamics and the Replacement of U. S. Infrastructures, in J. H. Ausubel and R. Herman, eds., *Cities and Their Vital Systems: Infrastructure Past, Present, and Future*. National Academy Press, Washington, D.C., 1988.
26. U. S. Department of Commerce. *Minerals Yearbook*. Bureau of Mines, Washington, D.C., 1901–1985 editions.
27. U. S. Department of Commerce. *Marketing Gypsum Products*. Bureau of Mines, Information Circular 6154, Washington, D.C., 1929.
28. J. A. Schumpeter. *The Theory of Economic Development*. Harvard University Press, Cambridge, Mass., 1934.
29. R. M. Solow. Technical Change and the Aggregate Production Function. *Review of Economics and Statistics*. 1957, pp. 312–20.
30. R. J. Nelson and S. G. Winter. *An Evolutionary Theory of Economic Change*. Harvard University Press, Cambridge, Mass., 1982.
31. D. J. Santini. A Model of Economic Fluctuations and Growth Arising from the Reshaping of Transportation Technology. *The Logistics and Transportation Review*. 1988, pp. 121–151.
32. A. E. Andersson. The Fourth Logistics Revolution. *Papers of the Regional Science Association*. 1986, pp. 1–12.
33. W. L. Garrison. Using Technology to Improve Transportation. *Transportation for the Future*. Springer-Verlag, pp. 87–122.
34. E. von Hipple. *The Sources of Innovation*. Oxford University Press, New York, 1988.
35. T. P. Hughes. *American Genesis: A Century of Innovation and Technological Enthusiasm*. Viking, New York, 1989.
36. R. R. Souleyrette. *Transportation Services and Innovation in the Housing Industry: A Study of the Relations Between Transportation and Production*. Ph.D. Thesis, Department of Civil Engineering, University of California, Berkeley, 1989.

Publication of this paper sponsored by Committee on the Application of Economic Analysis to Transportation Problems.