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Innovation and Technical Change in the Railroad Industry

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I. Introduction

The importance of innovation and technical change to the railroad industry is widely recognized. In a recent paper, Healy has gone so far as to suggest that, under present conditions, they may be of paramount importance.

> Because of the erosion of the other aspects of authority and responsibility, and the simultaneous appearance of major technological advances in other types of transportation, the responsibility for technological innovation among the various remaining responsibilities of management has become paramount. It is not an overstatement to say that both the place of railroads as a whole in the total transport picture and their individual economic success depend more than anything else upon the technological advances which managements develop and put into effect.[1]

Granting the significance of technical change, the following important questions arise concerning the extent of the technological advances that have occurred in recent years in the railroad industry and the process by which such advances have been introduced and have gained acceptance. How rapidly have labor and total factor productivity been increasing in the railroads? How rapidly has the production function shifted over time? How have important inventions in the railroad industry been distributed over time? Have the largest railroads tended

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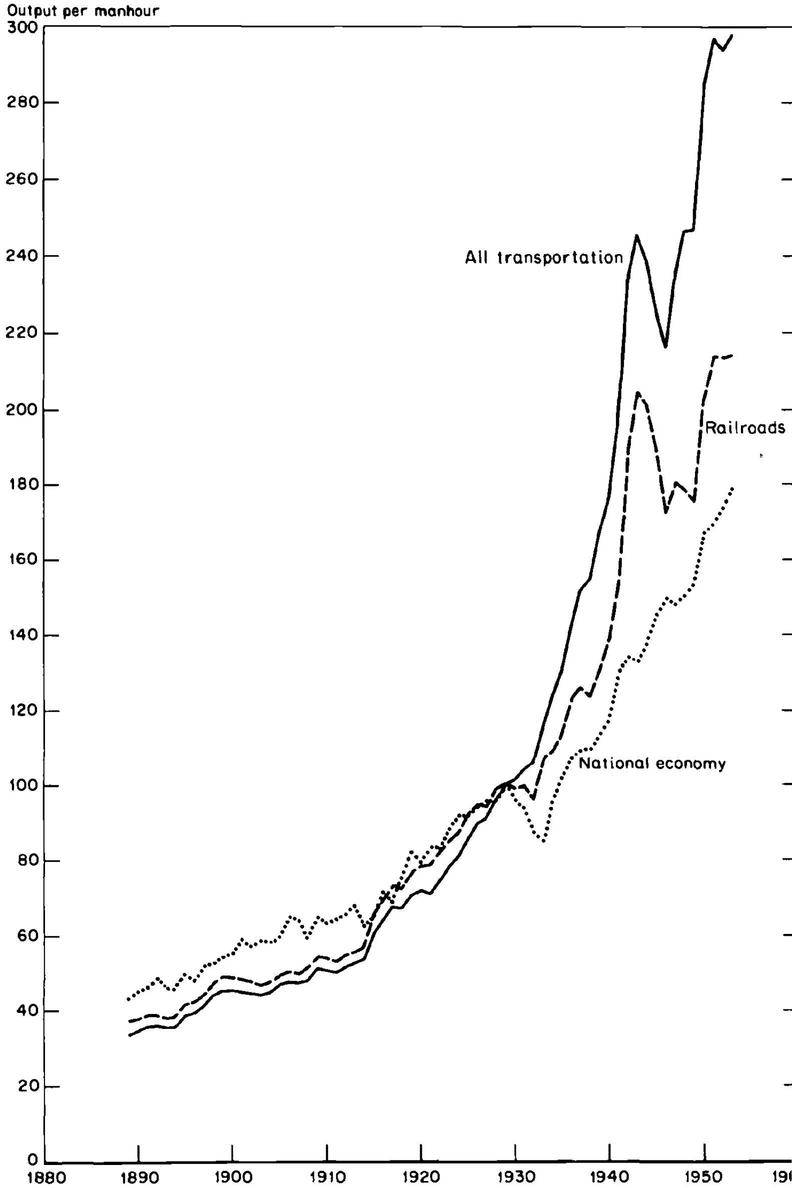
[1] K. Healy, "Management and Technological Change," in *Technological Change and the Future of the Railways*, Evanston, 1961, p. 126.

Figure 1

Output Per Man-Hour: Railroads, All Transportation, and National Economy, 1889–1953 (1929 = 100)



SOURCE: Kendrick, *Productivity Trends.*

to be the pioneers in introducing these new techniques? Once a new technique is introduced by one company, what determines how rapidly other companies take it up? What determines how rapidly its use spreads within a company? Specifically, what sorts of innovation have occurred in recent years in railroading? What prospective changes in technology seem most promising and what effects are they likely to have on railroad employment?

II. Increases in Productivity

There is an enormous literature concerned with the uses and misuses of average productivity measures—labor, capital, and total. If technical change is defined as a shift in the production function, it is generally agreed that increases in output per man-hour and in output per total factor input are incomplete measures of the rate of technical change.[2] Nonetheless, it is also agreed that, if properly used, they provide valuable, if only partial, information regarding changes over time in an industry's input requirements.

Figure 1 shows the pre-1954 movement in the railroad industry of output per man-hour, the most widely used average productivity measure. Between 1890 and 1925, output per man-hour went up about as rapidly in the railroad industry (2.5 per cent per year) as in all transportation (2.6 per cent per year),[3] but much more rapidly than in the economy as a whole (2.0 per cent per year). Between 1925 and 1953, although output per man-hour continued to rise more rapidly in railroads (3.0 per cent per year) than in the economy as a whole (2.4 per cent per year), it rose much more slowly than in all transportation (4.5 per cent per year).[4]

[2] It is obvious that changes in output per man-hour generally do not measure shifts in the production function. Moreover, only under quite restrictive conditions do changes in output per total factor input measure shifts in the production function (see E. Domar, "On Total Productivity and All That," *Journal of Political Economy*, December 1962).

[3] Of course, in view of the fact that the railroads were then such a large proportion of the transportation industry, this is what one would expect.

[4] These growth rates (and all others in this section) are only approximate, since they were computed by finding the rate of growth of output per man-hour between the initial and terminal years, ignoring the intermediate years. Nonetheless, they are reasonably adequate approximations and good enough for present purposes. Note too, when examining Figures 1 and 2, that the railroads have been operating at less than full capacity.

For discussions of various types of productivity measures, see *Output, Input, and Productivity Measurement*, Studies in Income and Wealth 25, Princeton University Press for National Bureau of Economic Research, 1961; and J. W. Kendrick, *Productivity Trends in the United States*, Princeton for NBER, 1961. For discussions

Over the entire period, 1890–1953, output per man-hour rose, on the average, about 2.8 per cent per year in the railroad industry. This increase was due partly to increases in the amount of capital utilized per man-hour. According to Kendrick's figures, the capital-labor ratio increased by about 50 per cent between 1890 and 1953. It was also due partly to changes in technology. Diesel locomotives replaced steam locomotives, automatic hump yards replaced flat yards, centralized traffic control and other signaling devices were introduced, mechanization of maintenance-of-way became important, and countless other improvements were made.[5]

Comparing years (1889, 1899, 1909, 1920, 1929, 1941, and 1950) when the railroad industry was operating at fairly high levels of capacity utilization, in an effort to exclude the effects of the business cycle, we find that apparently output per man-hour in the industry increased at a fairly steady rate through that long period. This is interesting, since one might suppose, with Fabricant and others,[6] that output per man-hour would tend to increase at a decreasing rate as an industry matured. These data, however, provide no indication of that.[7]

Figure 2 shows the long-term movement in the railroad industry of output per total factor input. Whereas data on output per man-hour take no account of changes over time in the amount of capital utilized per man-hour, the data in Figure 2 do take account of such changes, total factor input being a weighted combination of labor and capital inputs. The results indicate that output per total factor input rose more rapidly during 1890–1953 in the railroad industry (2.6 per cent per year) than in the economy as a whole (1.7 per cent per year), but less rapidly than in all transportation (3.1 per cent per year). Of

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of railroad productivity indexes, see H. Barger, *The Transportation Industries, 1889–1946*, New York, NBER, 1951; D. Munby, "The Productivity of British Railways," D. W. Glassborow, "The Comparison of Partial Productivity Ratios for National Railway Systems," and M. E. Paul, "International Productivity Comparisons Over Time," all in *Bulletin of Oxford Institute of Statistics*, Feb. 1963; and E. Mansfield and H. Wein, "Notes on Railroad Productivity and Efficiency Measures," *Land Economics*, Feb. 1958.

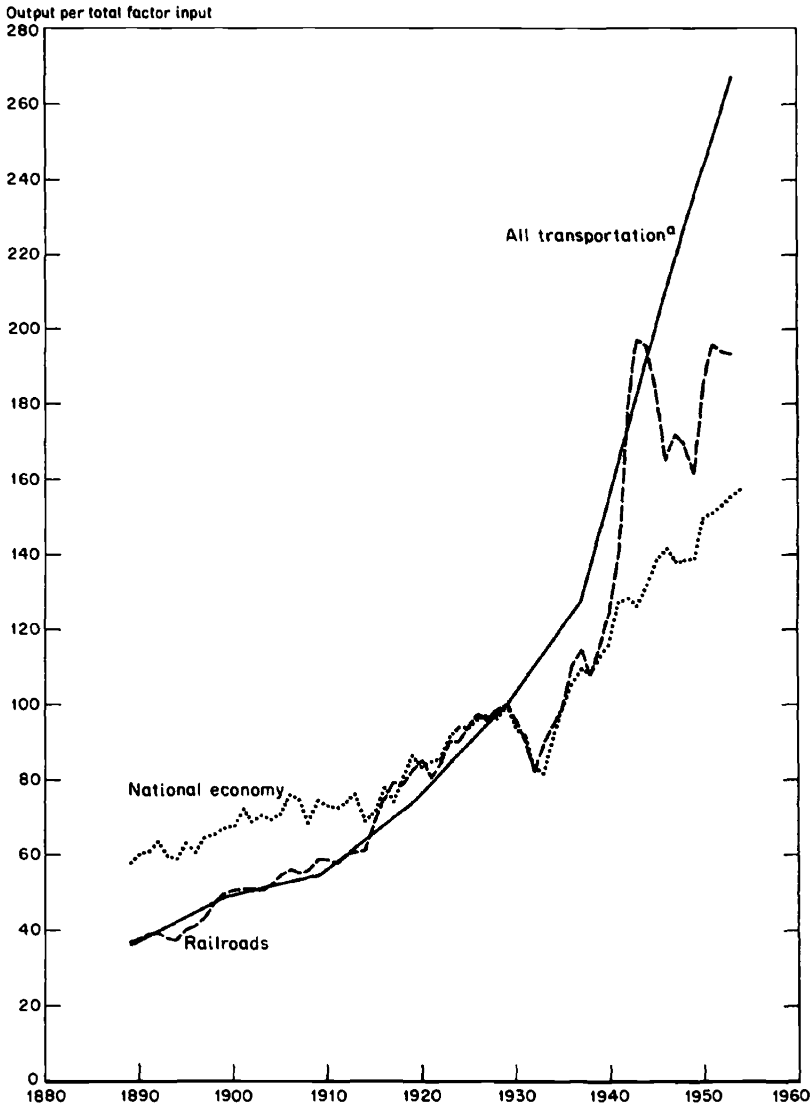
[5] Kendrick, *Productivity Trends*, pp. 543–545, contains the data on which the figure in the text is based. For a detailed discussion of recent increases in railroad efficiency, see J. Nelson, *Railroad Transportation and Public Policy*, Washington, 1959, Chap. 8.

[6] S. Fabricant, *The Relations Between Factory Employment and Output since 1899*, Occasional Paper 4, New York, NBER, 1941.

[7] The rates of growth of output per man-hour (in per cent) were: 2.7 (1889–99), 1.1 (1899–1909), 3.3 (1909–20), 2.7 (1920–29), 3.6 (1929–41), 3.1 (1941–50), and 2.6 (1950–57). There is no indication of a decrease over time. This has also been pointed out by H. Barger, *The Transportation Industries*, p. 95.

Figure 2

Output Per Total Factor Input: Railroads, All Transportation, and National Economy, 1889–1953 (1929 = 100)



SOURCE: Kendrick, *Productivity Trends.*

[a] Figures are given at only about ten-year intervals. The graph simply connects these points.

course, the more rapid increase in nonrailroad transportation may have been due partly to exclusion of government inputs like highways. Excluding years of deep depression and war, the rate of increase remained fairly steady in the railroad industry, the results being similar to those based on output per man-hour.[8]

Finally, a word should be added on the changes in railroad productivity since 1953. According to the Bureau of Labor Statistics, output per man-hour increased by about 5.8 per cent per year in the railroad industry during 1953–61. This was a much greater increase than had occurred previously in the railroads (3.0 per cent per year in 1925–53) or simultaneously in the private economy as a whole (2.7 per cent per year in 1953–61). The new techniques that helped to bring about the spurt in railroad productivity are described in Section VIII.

III. Shifts in the Production Function

Technical change is defined here as a shift in the production function. To measure such shifts in the railroad industry during 1917–59, I shall use the following highly simplified model, which was first employed by Solow[9] to analyze economy-wide data. First, I assume that all technical change in the railroad industry was capital embodied. To become effective, all innovations had to be embodied in new plant and equipment. Second, I assume that, for capital installed at time v which is still in existence at time t, the production function was

$$Q_v(t) = \beta e^{\lambda v} L_v(t)^\alpha K_v(t)^{1-\alpha}, \tag{1}$$

where $Q_v(t)$ is the output derived at time t from this capital, $L_v(t)$ is the amount of labor used at time t in combination with this capital, $K_v(t)$ is the amount of such capital in existence at time t, and λ is the rate of technical change. Note that Equation 1 implies that technical change was neutral, that it proceeded at a constant rate throughout the period, and that there were constant returns to scale. Third, I assume that all capital, regardless of vintage, depreciated at a constant annual rate of δ and that at any point in time the industry's total labor force is allocated efficiently among various vintages of capital. Featherbedding of many kinds is allowed by the model, since the working labor force may be larger than the firms consider optimal. Moreover, the results are not affected if a certain (fixed) per cent of the total time put in by labor is useless "make work."

[8] The rates of growth of output per total factor input (in per cent) were: 3.1 (1889–99), 1.8 (1899–1909), 3.3 (1909–20), 1.8 (1920–29), 2.9 (1929–41), 2.9 (1941–50). Again, there is no evidence of a decrease over time.

[9] R. Solow, "Investment and Technical Progress," in *Mathematical Methods in the Social Sciences*, Arrow, Karlin, and Suppes, Eds., Stanford, 1960.

Given these assumptions, one can easily show that

$$Q(t) = \beta e^{-\delta(1-\alpha)t} L(t)^{\alpha} S(t)^{1-\alpha}, \tag{2}$$

where $Q(t)$ is the total output of the industry at time t, $L(t)$ is the total amount of labor used by the industry at time t, and

$$S(t) = \int_{-\infty}^{t} e^{\sigma v} I(v)\, dv,$$

where $I(v)$ is the industry's gross investment at time v, and $\sigma = \delta + \lambda/(1 - \alpha)$. Letting $R(t) = Q(t)^{1/(1-\alpha)} \div L(t)^{\alpha/(1-\alpha)}$, it follows that

$$\ln\left[\frac{\dfrac{dR(t)}{dt} + \delta R(t)}{I(t)}\right] = \frac{\ln \beta}{1 - \alpha} + \frac{\lambda t}{1 - \alpha}. \tag{3}$$

Thus, one can estimate λ—the rate of technical change—in the following way. First, using data regarding $Q(t)$, $L(t)$, and α, it is an easy matter to compute $R(t)$. Second, substituting $\Delta R(t)$ for $dR(t)/dt$ and inserting data regarding $I(t)$ and δ, one can estimate the left-hand side of Equation 3. Third, if the left-hand side of Equation 3 is regressed against time, the product of the regression coefficient and $(1 - \alpha)$ is an estimate of λ.

This procedure was used to estimate the rate of technical change in the railroad industry during 1917–59. Following Bowden,[10] $Q(t)$ was set equal to the number of ton-miles plus 2.6 times the number of passenger-miles for Class I line-haul railroads during year t, the result being expressed as an index number (1929 = 100).[11] $L(t)$ was "total time paid for" by class I line-haul railroads in year t,[12] the result being expressed as an index number (1929 = 100). $I(t)$, expressed in millions of 1929 dollars, was measured by Ulmer's figures[13] on gross investment

[10] W. Bowden, "Productivity, Hours, and Compensation of Railroad Labor," *Monthly Labor Review*, Dec. 1933, pp. 1277–1278. For those years for which Barger (*Transportation Industries*) provided data, I used his figures on $Q(t)$. Of course, railroad output is multidimensional and this output index is very crude. For an analysis of technical change which takes account of the multidimensionality of an industry's output, see V. Smith, "Engineering Data and Statistical Techniques in the Analysis of Production and Technological Change: Fuel Requirements of the Trucking Industry," *Econometrica*, Apr. 1957.

[11] Of course, $Q(t)$ really should be measured by value added, but I assume that value added is proportional to output.

[12] For those years for which Barger (*Transportation Industries*) provided data, I used his figures on $L(t)$. Although they pertain to time worked, rather than time paid for, the index numbers are not affected much by the difference. Figures for later years come from *Statistics of Railways*.

[13] M. Ulmer, *Trends and Cycles in Capital Formation by United States Railroads, 1870–1950*, Occasional Paper 43, New York, NBER, 1954. Also, see his *Capital in Transportation, Communications, and Public Utilities: Its Formation and Financing*, Princeton for NBER, 1960.

by railroads (1917–50) and the corresponding figures issued by the Department of Commerce (1951–57). Finally, the average value of labor's share of the industry's value added during 1946–57 was used as an estimate of α[14] and, following Ulmer (p. 49), .02 was used as an estimate of δ. Needless to say, these estimates are very rough.

The resulting regression, omitting cases where $\Delta R(t) + \delta R(t) < 0$, is

$$\ln\left[\frac{\Delta R(t) + \delta R(t)}{I(t)}\right] = -413 + \underset{(.020)}{.213t}. \qquad (r = .89) \tag{4}$$

The regression coefficient has the expected sign and is highly significant. Moreover, Figure 3 shows that this regression fits the data reasonably well. The regression coefficient multiplied by $(1 - \alpha)$, gives the estimate of λ, .030, its standard error being .003. This is higher than Solow's estimate of λ for the entire economy (.025), though the difference is probably statistically nonsignificant.

In Equation 4, I obviously had to omit cases where $\Delta R(t) + \delta R(t) < 0$. As Solow has pointed out, the omitted years tend to be those in which there was a serious drop in output; and this is a rough way of dealing with the fact that, although the model assumes the industry is always working up to capacity, obviously it has not been. As an experiment, I tried to handle this problem in another way. I obtained from various members of the industry rough estimates of the ratio of actual to capacity output and the ratio of actual to capacity labor requirements during each year.[15] Dividing $Q(t)$ by the former ratio and $L(t)$ by the latter, we obtain estimates of capacity output and capacity labor requirements. Using these figures rather than $Q(t)$ and and $L(t)$, we obtain the following regression:

$$\ln\left[\frac{\Delta R(t) + \delta R(t)}{I(t)}\right] = -23.8 + \underset{(.008)}{.007t}. \qquad (r = .00) \tag{5}$$

The regression coefficient is not statistically significant, and the fit is extremely poor. Apparently, the estimates of the ratios were too inaccurate to be useful in this sort of analysis.

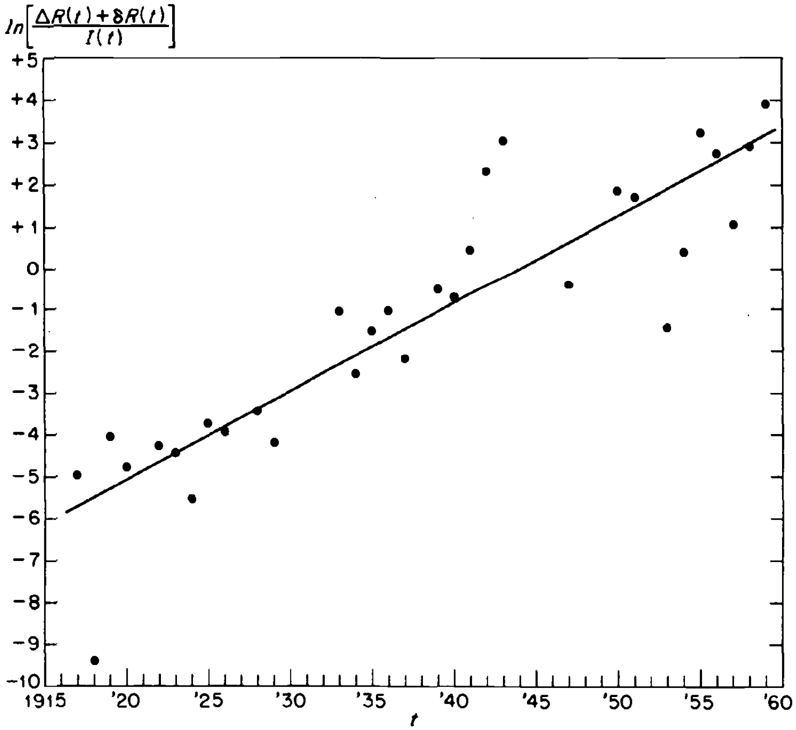
[14] In this model, as well as in the older ones where technical change was "disembodied," labor's share will equal α, if the value of labor's marginal product is set equal to the wage rate. Of course, in a regulated, highly unionized industry like railroads, this may not be a very suitable assumption. But the resulting estimate of α (.86) is very close to one made by L. Klein (.89) which rests on somewhat different assumptions (see L. Klein, *A Textbook of Econometrics*, Evanston, 1956, p. 234). These estimates are rough, but it is difficult to see what alternative procedures could have been used.

[15] These estimates were obtained in interviews with executives of several railroads and a railroad equipment company.

Figure 3

Plot of $\ln\left[\frac{\Delta R(t) + \delta R(t)}{I(t)}\right]$ Against t,

Railroad Industry, 1917–59



SOURCE: See Section III.

In conclusion, the rate of technical change in the railroad industry, as measured by λ, seemed to be about 3.0 per cent per year during 1917–59, which is higher—though perhaps not significantly so—than the corresponding estimate for the entire U.S. economy. Needless to say, the model underlying this estimate is oversimplified in some respects, and consequently the estimate, although reasonable, should be treated with caution.[16]

[16] Some of the difficulties are as follows: First, contrary to the model, technical change may not have been neutral, some of it may not have required new capital, there may have been economies or diseconomies of scale, labor inputs may not have been homogeneous over time and, once capital was installed, there may not have been the possibilities for capital-labor substitution envisaged in the model.

IV. Timing of Invention

The model in the previous section throws little light on the underlying processes of invention, innovation, and diffusion that are responsible for the estimated shifts in the production function. In this section, together with Sections V–VI, I turn to these processes. Specifically, the present section is concerned with the distribution over time of important railroad inventions, the object being to determine whether such inventions have been distributed in accord with various hypotheses put forth by Kuznets, Schmookler, and others.

At the outset, one should note that there are enormous problems in obtaining a meaningful and useful definition of an "invention" and in evaluating the contribution of a particular invention to an industry's technology. Results obtained are bound to be crude. The procedure adopted is to use Schmookler's chronology of patents and important railroad inventions and to analyze the distribution over time of all patents, all important inventions, and those considered by Schmookler to be "most important." Obviously, the findings can only be suggestive, since, as Schmookler points out, the data are very rough.[17]

Two hypotheses regarding the timing of invention have received considerable attention. First, there is the hypothesis, put forth by Kuznets, Burns, Fabricant, and others,[18] that the rate of occurrence of significant inventions decreases as an industry grows older. "Every technical improvement, by lowering costs and by perfecting the utilization of raw materials and of power, bars the way to further progress." [19]

Second, the railroads may have been operating off the production function during some of the period because of slack demand and inefficiencies. Third, the data used to estimate λ are rough. Fourth, technical change, as defined here, is a catchall that includes the effects of many factors other than the improvement of techniques (see E. Domar, "On the Measurement of Technological Change," *Economic Journal*, Dec. 1961, pp. 709–729).

Note too that the research and development underlying the technical change in the railroad industry have been carried out largely outside the railroad industry.

[17] J. Schmookler, "Changes in Industry and in the State of Knowledge as Determinants of Industrial Invention," in *The Rate and Direction of Inventive Activity: Economic and Social Factors*, Special Conference 13, Princeton for NBER, 1962. I am grateful to Schmookler for making his unpublished worksheets and the chronology of inventions used in his paper available to me.

[18] S. Kuznets, *Secular Movements in Production and Prices*, Boston, 1930; A. F. Burns, *Production Trends in the United States Since 1870*, New York, NBER, 1934; S. Fabricant, *Factory Employment and Output;* and J. Wolf, *Die Volkswirtschaft der Gegenwort u. Zukunft*, Leipzig, 1912.

[19] Quoted from *ibid.*, by Kuznets, *Secular Movements in Production and Prices*, p. 11.

Second, there is the hypothesis, put forth by Schmookler, that significant inventions tend to occur during periods when investment is high. "The trend and swings of invention are probably caused . . . by those in investment or by the same forces which dominate the latter." [20]

To test these hypotheses, we regress the number of inventions in year t on the amount of railroad capital formation (in millions of 1929 dollars) in year $(t - 3)$ and on t. A three-year lag is used for the investment variable, because this is the lag adopted by Griliches and Schmookler.[21] For all of Schmookler's "important" inventions, the results are:

$$n(t) = 39.0 + \underset{(.0004)}{.0011I(t-3)} - \underset{(.0048)}{.0200t}, \qquad (r = .46) \tag{6}$$

where $n(t)$ is the number of these inventions occurring in year t, and $I(t)$ is the railroad capital formation in year t. Figure 4 contains the time series of $n(t)$. Letting $n(t)$ be the "most important" inventions, the results are

$$n(t) = 14.1 - \underset{(.00029)}{.00003I(t-3)} - \underset{(.0034)}{.0071t}. \qquad (r = .17) \tag{7}$$

Letting $n(t)$ be the number of patents, the results are

$$n(t) = 4510 + \underset{(.223)}{.936I(t-3)} - \underset{(2.63)}{2.04t}. \qquad (r = .41) \tag{8}$$

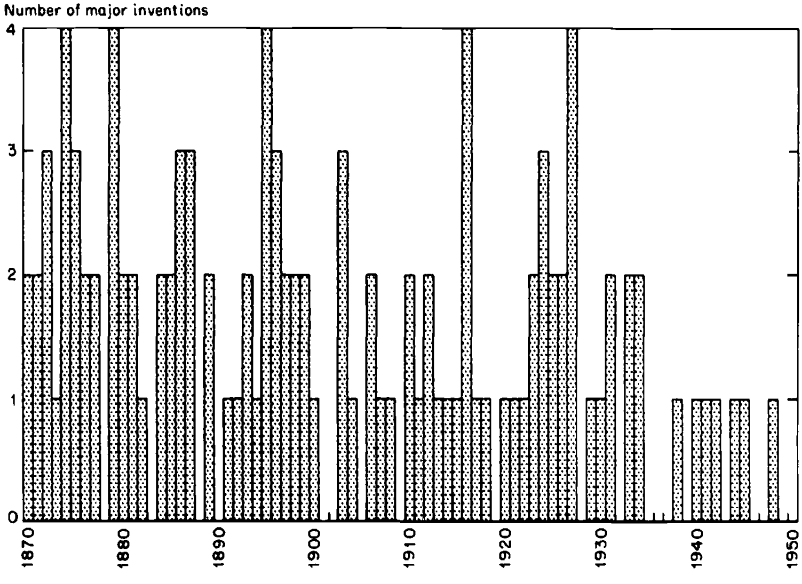
The results are usually in accord with the hypothesis of Kuznets, Burns and Fabricant, the regression coefficient of t being negative and statistically significant in two of the equations. The results are also in general accord with the Schmookler hypothesis, the regression coefficient of $I(t - 3)$ being positive and statistically significant in two of the equations. Of course, it may be objected that the number of inventions in each year should be weighted by some measure of importance. But

[20] Schmookler, "Changes in Industry," p. 215. Note that Schmookler's tests of this hypothesis are based on the same data used here, but the methods are entirely different.

[21] Z. Griliches and J. Schmookler, "Inventing and Maximizing," *American Economic Review* (September 1963). Their data do not pertain to the railroads and their techniques are different.

We use the period 1870–1950, because annual data on $I(t)$ do not seem to be available for earlier years and because of the particularly great difficulties in evaluating the importance of very recent inventions. Besides the regressions shown below, regressions including t^2 as an independent variable, as well as t and $I(t)$, were run. The effect of t^2 is not significant.

Figure 4
Number of Major Railroad Inventions, Schmookler's Chronology, 1870–1950



SOURCE: Schmookler, "Changes in Industry and in the State of Knowledge.'

if Schmookler's weights[22] (by technological and economic importance) are used in Equation 7, the results change very little. Unfortunately, such weights are not available for Equations 6 and 8.[23]

It is interesting that, although the probability of a major invention has decreased over time, the rate of productivity increase has not slowed down. Perhaps the rate of invention has decreased substantially only in fairly recent years and it has not yet had an effect on the rate of productivity increase. The data in Figure 3 seem to suggest that $n(t)$

[22] Schmookler, "Changes in Industry."

[23] In addition, I ran Cox's test of randomness against trend. The results indicate a downward trend. See D. Cox, "Some Statistical Methods Connected with Series of Events," *Journal of the Royal Statistical Society*, 1955; and E. Mansfield, "Power Functions for Cox's Test of Randomness Against Trend," *Technometrics*, Aug. 1962.

With regard to Schmookler's hypothesis, it should be noted that if $I(t)$, rather than $I(t - 3)$, is used, it is not statistically significant in Equations 6 or 7, but it is statistically significant in Equation 8. It is also interesting that Schmookler's hypothesis holds most strongly for relatively unimportant inventions. This seems reasonable to me and I suspect it is true in other industries as well.

was lower during 1930–50 than previously, and that the trend in $n(t)$ was relatively slight before 1930.[24]

V. Size of Innovators

The importance of the innovator—the firm that first introduces a new technique commercially—has been stressed by Schumpeter and others. Is it true, as Schumpeter claimed, that the innovators in recent years have tended to be very large firms? Have the largest firms been the first to introduce a disproportionately large share of important new techniques? This section is concerned with these questions, which are obviously important from the point of view of public policy, and which throw further light on the process of technical change in the railway industry.

First, consider the extent to which the largest railroads have been the innovators. Healy[25] includes the following in a list of ten major innovations introduced in the railroad industry since 1920: (1) four-wheel trailing trucks and large fire box for steam locomotives, (2) the diesel-electric switcher, (3) the diesel-electric passenger locomotive, (4) the diesel-electric freight locomotive, (5) the roller bearing, (6) the streamlined, lightweight passenger car, (7) the AB freight airbrake, (8) air conditioning, (9) car retarders, and (10) centralized traffic control. Taking this very small sample of innovations, I determined which firm was first to introduce each one and the size distribution of the innovators.[26]

The results, shown in Table 1, seem to support the Schumpeterean view. Almost all the innovators were among the ten largest firms, and

[24] Although there was some downward trend in $n(t)$ before 1930, it was relatively slight. Only after 1930 was there an appreciable drop. This would seem to be in accord with the hypothesis in the text, but another possible explanation is that it is very difficult to gauge the importance of recent inventions, and many important ones are omitted from the list. Moreover, the general decline in patenting may have been important too.

For some tentative results regarding the timing of innovations—not inventions—and their effect on investment, see E. Mansfield, "Timing of Innovation and the Investment Function," Carnegie Institute of Technology, 1963.

[25] K. Healy, "Regularization of Capital Investment in Railroads," in *Regularization of Business Investment*, Special Conference 4, Princeton for NBER, 1954.

[26] The innovator is defined as the first firm to introduce an innovation commercially. The identity of the innovator in each case was determined by a careful search of past issues of trade journals like *Railway Age*. Of course, there may be arguments over the definitions of "the innovation" and "commercially." Although it is possible that some of the information is incorrect, it is unlikely that there are any errors of real consequence.

TABLE 1

SIZE DISTRIBUTION OF INNOVATORS AND ALL CLASS I RAILROADS

Size of Firm (millions of ton-miles, 1920)	Number of: Firms	Innovations[a]	Innovators
	A. EACH SYSTEM REGARDED AS A UNIT		
Less than 4,000	77	0.0	0
4,001 - 8,000	6	0.0	0
8,001 - 12,000	7	0.0	0
12,001 - 16,000	8	3.0	3
16,001 - 20,000	3	0.5	1
20,000 and over	3	6.5	3
	B. INDIVIDUAL CLASS I LINE-HAUL RAILROADS[b]		
Less than 4,000	159	1.0	1
4,001 - 8,000	9	0.0	0
8,001 - 12,000	12	2.0	2
12,001 - 16,000	4	1.0	1
16,001 - 20,000	1	0.5	1
20,000 and over	3	4.5	3

Source: See Section 5.

[a] When two firms began using an innovation at about the same time, the credit was split equally between them. Thus, fractions occur in this column.

[b] There is one less innovation in this part of the table than in the upper part, because one of the innovators, although part of a very large system, was not a Class I line-haul railroad.

about one-half were among the four largest. Moreover, although the largest four firms account for about 32 per cent of the industry's ton-miles, they account for 65 per cent of the innovations. Thus, if one assumes that these innovations are a representative sample, the largest four firms accounted for a significantly larger share than would be expected on the basis of their share of the freight traffic. By this criterion, their share of the innovations was disproportionately large.[27]

[27] The chances are less than .05 that the observed difference (between .65 and .32) is due to chance. Of course, no attempt is made to weight the small numbers of innovations included in Table 1 by their importance. Moreover, the smaller, less important innovations are excluded altogether. The results in Table 1 can only be regarded as a very rough, partial measure of the size distribution of the innovators. Note too that the criterion used to judge whether the largest firms' share is disproportionately large is not the only one that could have been used. But it seems to be a reasonable one.

In Table 1, two different definitions of a firm are used. In the upper panel, an entire system is regarded as a single unit. Thus, the firms are either entire systems or Class I line-haul railroads that do not belong to any system. In the lower panel, each Class I line-haul railroad is regarded as a single unit, whether or not it belongs to a system.

Next, consider a simple model designed to explain why the largest firms in some industries but not in others do a disproportionately large share of the innovating. Since this model, which I have described in more detail elsewhere,[28] seems to work reasonably well for other industries, it is of interest to determine how well it can explain our results for the railroads. Consider all innovations introduced during a given period in a particular industry which required, for their introduction, a minimum investment of I. Letting $\pi_j(I)$ be the proportion of these innovations introduced by the j^{th} firm in this industry, the model assumes that

$$\pi_j(I) = \begin{cases} 0 & S_j \geq M \\ B_1(I) + B_2(I)S_j + E_j(I) & S_j \geq M \end{cases}, \tag{9}$$

where S_j is the size (measured in terms of assets) of the j^{th} firm. Of course, $B_1(I)$, $B_2(I)$, and M vary among industries and time periods, $B_2(I)$ is non-negative, and $E_j(I)$ is a random error term.[29]

Firms below a certain size (M) introduce none of the innovations because they lack the volume of production required to use the innovation profitably.[30] For firms larger than M, we suppose that the proportion of these innovations introduced by a firm is a direct, linear function of its size. In addition, we assume that a firm's size has more effect on $\pi_j(I)$ if the innovations require relatively large investments than if they can be introduced cheaply. Consequently,

$$B_2(I) = a_1 + a_2 I/\bar{S}_M + z, \tag{10}$$

where $\bar{S}_M$ is the average assets of the firms with assets greater than or equal to M, a_2 is presumed to be positive, and z is a random error term.

It follows that the proportion of all the innovations carried out by the four largest firms equals

$$\pi = 4/N(M) + 4a_1(\bar{S}_4 - \bar{S}_M) + 4a_2\bar{I}(\bar{S}_4 - \bar{S}_M)/\bar{S}_M + z', \tag{11}$$

where $N(M)$ is the number of firms with assets greater than or equal to M, $\bar{S}_4$ is the average assets of the four largest firms, $\bar{I}$ is the average minimum investment required to introduce these innovations, and z'

[28] E. Mansfield, "Size of Firm, Market Structure, and Innovation," *Journal of Political Economy* (December 1963).

[29] It may turn out that $\pi_j(I)$ is a linear function of $S_j/\sum_{s_j>M} S_j$, rather than S_j. If so, the modifications required in the subsequent analysis are straightforward. See Mansfield, "Size of Firm."

[30] For simplicity, I assume that M is the same for all innovations. Although it complicates things, it is possible to allow for differences among innovations in M.

is a random error term.[31] Inserting estimates of a_1 and a_2 obtained from a study of the steel and petroleum industries,[32] we have

$$\pi = 4/N(M) + .0014(\bar{S}_4 - \bar{S}_M) + .0289\bar{I}(\bar{S}_4 - \bar{S}_M)/\bar{S}_M + z'. \qquad (12)$$

To what extent can this equation, based on experience in the steel and petroleum industries, predict the behavior of the largest four firms in the railroad industry? Since the value of π derived from Table 1 could, with reasonable probability, depart from the true value by as much as .25, simply because of sampling errors, it is clear that a test of this sort will not be very powerful. Nonetheless, it is worth carrying out. Ignoring z', the estimate of π obtained from Equation 12 is .54,[33] which is reasonably close to .65, the value of π derived from Table 1. Thus, taking account of the independent variables in Equation 12, it appears that, in comparison with other industries, the estimate of the largest four railroads' share of the innovations is higher than would be expected, but that the difference could easily be due to chance. Data of the sort presented in Table 1 will have to be gathered for more railroad innovations if we are to tell whether this difference is due merely to sampling variation or whether there is a real difference in this regard between the railroads and other industries.[34]

VI. Interfirm Rates of Diffusion

Once one firm introduced a new technique, how soon did others in the railroad industry come to use it? Apparently, twenty years or more elapsed before all major railroads began to use many of the important twentieth century innovations in locomotives, signaling, and yards. In particular, it took about fifteen years for the diesel locomotive,

[31] This also assumes that $\sum_j E_j(I) = 0$. Note that $\bar{S}_4$, $\bar{S}_M$, and $\bar{I}$ are expressed in millions of 1950 dollars.

[32] Mansfield, "Size of Firm, Market Structure, and Innovation." Of course there could be an identification problem in equation (11) (see my discussion in *ibid.*).

[33] To obtain this number, we needed rough estimates of M, $\bar{S}_M$, $\bar{S}_4$, and $\bar{I}$. As a very rough estimate of M, 5 billion ton-miles in 1920 were used. (Although this is not measured in terms of assets, it makes no difference.) To estimate $\bar{S}_M$ and $\bar{S}_4$, the average ton-miles of (1) all firms with more than 5 billion ton-miles, and (2) the four largest firms were each multiplied by the average ratio of total assets to ton-miles for the ten largest firms. As a rough estimate of $\bar{I}$, \$1 million was taken. Although these estimates are crude they should not be too wide of the mark. To convert them from 1920 to 1950 dollars, they were multiplied by the ratio of the 1950 to the 1920 ENR construction index. Note too that systems are used here as individual firms.

[34] Note that there are sampling errors in the estimates of a_1 and a_2, as well as in in the estimate of π.

twenty-five years for the mikado locomotive, twenty years for the four-wheel trailing truck locomotive, twenty-five years for centralized traffic control, and thirty years for car retarders.[35]

What determines how rapidly a particular innovation spreads from one company to another? According to a simple model presented elsewhere,[36] the probability that a firm will introduce a new technique is an increasing function of the proportion of firms already using it and the profitability of doing so, but a decreasing function of the size of the investment required. Given these assumptions, and some additional ones of a technical nature,[37] it can be shown that

$$g_i^{-1} = u_0 + u_1 p_i + u_2 s_i + z_i'', \tag{13}$$

where g_i is a measure of the rate of diffusion (the number of years that elapsed between the time when 10 per cent of the major firms had introduced the i^{th} innovation and the time when 90 per cent had done so), p_i is a measure of the relative profitability of the i^{th} innovation (the average payout period required to justify investments during the relevant period divided by the average payout period for investment in the i^{th} innovation), s_i is a measure of the size of the investment required (the average initial investment in the innovation as a per cent of the average total assets of the firms), and z_i'' is a random error term.[38]

Inserting estimates of the u's based on data pertaining to a dozen innovations, the resulting equation is

$$g_i^{-1} = \begin{Bmatrix} -.066 \\ -.130 \\ -.118 \\ -.134 \end{Bmatrix} + \underset{(.034)}{.121 p_i} - \underset{(.0032)}{.0061 s_i} + z_i'', \qquad (r = .997) \tag{14}$$

where the top figure in brackets pertains to the brewing industry, the next to bituminous coal, the following to iron and steel, and the bottom figure pertains to the railroads. Ignoring z_i'', this equation, which is plotted in Figure 5 for the railroad industry, can represent the data for

[35] E. Mansfield, "Technical Change and the Rate of Imitation," *Econometrica*, Oct. 1962, pp. 741–766; Healy, "Regularization of Capital Investment."

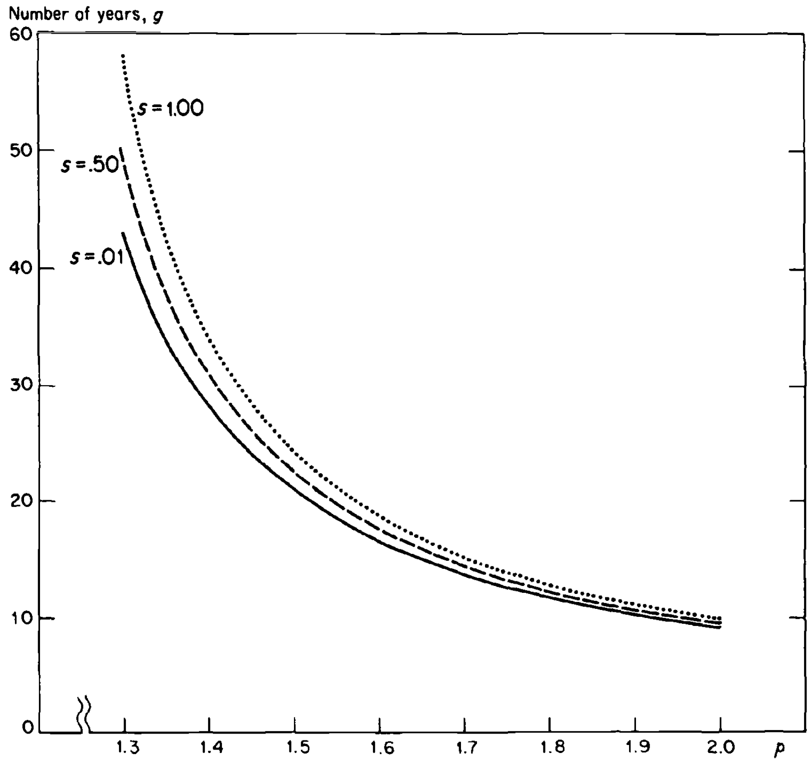
[36] Mansfield, "Technical Change."

[37] *Ibid.*, pp. 747–748.

[38] Actually, g_i is not used in *ibid.* as a measure of the rate of diffusion, but the measure used there is too complicated to be taken up here. The spirit and most of the substance of the original argument can be conveyed by using g_i, rather than the original measure. Equations 13 and 14 were derived from the original equations by using the theoretical relationship between g_i and the original measure.

Figure 5

Average Number of Years Between Introduction of an Innovation by 10 Per Cent and 90 Per Cent of Major Railroads, Given Relative Profitability of Innovation (p) and Relative Size of Necessary Investment (s)



SOURCE: Equation 14.

these innovations very well. Apparently, for these innovations, differences in p_i and s_i explain almost all the variation in the rate of diffusion within a particular industry.[39]

Comparing these various industries, p_i and s_i being held constant, the average rate of diffusion in the railroad industry seems slower than

[39] Besides p_i and s_i, several additional variables were included—the durability of old equipment, the rate of expansion of the industry, the phase of the business cycle when the innovation was introduced, and a trend factor. Although the effects of all of these factors on g_i seemed to be in the expected direction, none of them was statistically significant.

in iron and steel, bituminous coal, and brewing. For example, if $p_i = 1.5$ and $s_i = .50$, the average time span between 10 and 90 per cent of full introduction seems to be six years shorter in steel than in the railroads, two years shorter in coal, and fourteen years shorter in brewing. However, although the difference between the railroads and brewing is highly significant, the differences among the railroads, coal, and steel could be due to chance. To the extent that they exist, these differences may be due in part to the conservatism of railroad management, the financial ill-health of the industry, and the attitude of railway labor.[40]

Finally, what sorts of railroads tend to be relatively quick to begin using new techniques, and what sorts tend to be relatively slow? To judge from data on the diffusion of fourteen innovations (five from the railroad industry), the speed with which a particular firm begins using a new technique is directly related to its size and the profitability of its investment in the technique. But a firm's rate of growth, its profit level, its liquidity, its profit trend, or the age of its management seem to have no consistent or close relationship with how soon a firm adopts an innovation. Moreover, in the railroad industry (and in most others that could be studied), only a relatively weak tendency existed for the same firms to be consistently the earliest to introduce different innovations. The leaders in the case of one innovation are quite often followers for another, especially if the innovations become available at widely different points in time.[41]

VII. Intrafirm Rates of Diffusion

The previous section is concerned with the rate at which firms in the railroad industry begin to use new techniques. This section examines

[40] For some discussion of the attitude of railway labor toward technological change, see W. Haber, "Technological Innovation and Labor in the Railway Industry," in *Technological Change and the Future of the Railways*, Evanston, 1961; and, in the same volume, G. Brown, "The Attitude of Labor Toward Technological Change in the Railway Industry." Also included in that volume are relevant papers by J. Nelson ("Technological Change and the Railway's Need for Capital") and W. Cottrell ("Sociological Barriers to Technological Change").

[41] For a detailed discussion of the factors influencing how rapidly a particular firm begins using a new technique, see E. Mansfield, "The Speed of Response of Firms to New Techniques," *Quarterly Journal of Economics*, May 1963. This study includes data on the iron and steel, bituminous coal, brewing, and railroad industries. Of course, there is no contradiction between the findings (1) that, holding the profitability of the innovation constant, the innovators tend to be large firms and (2) that there is only a fairly weak correlation between how rapidly a firm introduces one innovation and how rapidly it introduces another.

the influence of various factors on the intrafirm rate of diffusion,[42] the rate at which a firm, when it has begun to use a new technique, continues to substitute it for older methods. In particular, one of the most important recent innovations in railroading, the diesel locomotive, is singled out and a simple econometric model is described, which explains a considerable portion of the observed differences among railroads in the

TABLE 2

TIME INTERVAL BETWEEN DATES WHEN DIESEL LOCOMOTIVES WERE 10 PER CENT AND 90 PER CENT OF ALL LOCOMOTIVES, THIRTY CLASS I RAILROAD SYSTEMS

Time Interval (years)	Number of Class I Railroad Systems
14 or more	3
11-13	7
8-10	11
5- 7	3
3- 4	6
Total	30

Source: *Statistics of Railroads,* 1925-61.

Note: Among the 30 Class I railroad systems, entire systems are included as single units.

rate at which, after first introducing it, they substituted diesel motive power for steam.

Table 2 shows, for thirty randomly chosen Class I railroads, the number of years that elapsed between the time when each road's diesels constituted 10 per cent of its locomotive stock, and the time when they constituted 90 per cent of its locomotive stock. Although this is a crude measure of the intrafirm rate of diffusion, it is a reasonable first approximation. According to the table, there was great variation among railroads in that rate. Although nine years were required on the average to increase a firm's stock of diesels from 10 to 90 per cent of the total, six firms took only three or four years and three took fourteen years or more.[43]

[42] A more complete description of the results contained in this section is presented in E. Mansfield, "Intrafirm Rates of Diffusion of an Innovation," *Review of Economics and Statistics*, November 1963.

[43] Of course, this is a crude measure, for several reasons. First, it is based on ownership, not utilization, data. Second, it does not distinguish between various

The following model will help explain the differences. Let $D_i(t)$ be the number of diesel locomotives owned by the i^{th} firm at time t, N_i be the number of steam locomotives owned by the firm before it began to dieselize, and r_i be the number of steam locomotives replaced by a single diesel. Assuming that the i^{th} firm's traffic volume and r_i remain approximately constant during the relevant period,[44] the total number of locomotives owned by the i^{th} firm at time t is

$$t_i(t) = N_i - (r_i - 1)D_i(t). \tag{15}$$

Since the firm will therefore employ N_i/r_i diesel locomotives when fully dieselized, there are $[N_i/r_i - D_i(t)]$ places left to be filled with diesels at time t.

Let ρ_i be the rate of return the i^{th} firm could obtain by filling one of these places with a diesel locomotive (assuming for simplicity that this rate of return is the same for all places and all t); L_i be the time interval (in years) separating the year when the first firm (in this country) "began"[45] using diesel locomotives from the year when the i^{th} firm "began" using them; S_i be a measure of its size (its freight ton-miles in 1949); and C_i be a measure of its liquidity at the time it "began" to dieselize (its current ratio). Letting

$$W_i(t) = [D_i(t+1) - D_i(t)]/[N_i/r_i - D_i(t)], \tag{16}$$

we suppose that

$$W_i(t) = f(\rho_i, L_i, r_iD_i(t)/N_i, S_i, C_i, \ldots). \tag{17}$$

The rationale for this hypothesis is as follows: Other things equal, one would expect $W_i(t)$—the proportion of unfilled places that were filled with a diesel locomotive during the period—to be directly related to ρ_i and inversely related to the apparent riskiness of the investment. Since the latter cannot be measured directly, we assume: (1) the longer a firm waited before "beginning" to use the diesel locomotive, the more knowledge it had regarding its profitability when it "began" to dieselize; and (2) the nearer a firm was to full dieselization at time t (i.e., the

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kinds of services, e.g., switching, freight. Third, it is based on the arbitrary choice of 10 and 90 per cent. If we use a better measure based on utilization data for freight service, however, we find there are still considerable differences among firms in the intrafirm rate of diffusion, although not so large as in Table 2. Moreover, the model described below is about as useful in explaining these data as those in Table 2.

[44] This is only a first approximation, but data indicate that it is reasonably accurate during the relevant period of time.

[45] The date when a firm "began" to dieselize is the date when 10 per cent of its locomotives were diesels.

greater was $r_iD_i(t)/N_i$), the less was its uncertainty at time t relative to its uncertainty when it "began" to dieselize. In addition, because the more liquid firms were better able to finance the necessary investment and to take the risks, one might expect them, all other things being equal, to have invested more heavily than other firms had. Finally, smaller firms might have been expected to convert to diesels more rapidly than larger ones because of the costliness of operating two kinds of motive power in a small system, because of the smaller absolute investment required to convert, and perhaps because of the quicker process of decision making in smaller units.

We assume that $W_i(t)$ can be approximated within the relevant range by a quadratic function of $\rho_i, L_i, \ldots, C_i$, but that the coefficient of $[r_iD_i(t)/N_i]^2$ is zero. Then, substituting the corresponding differential equation for the difference equation that results, and recognizing that $\lim_{t \to -\infty} D_i(t) = 0$, it can be shown that

$$4.39Q_i^{-1} = \phi_0 + \phi_1\rho_i + \phi_2L_i + \phi_3S_i + \phi_4C_i + z_i''', \tag{18}$$

where z_i''' is a random error term and Q_i is the time interval between the date when 10 per cent of the i^{th} firm's locomotives were diesels and the date when 90 per cent of them were diesels.[46] Using rough estimates of ρ_i,[47] it was possible to estimate the ϕ's, the result being

$$4.39Q_i^{-1} = -.163 + \underset{(.492)}{.900}\ \rho_i + \underset{(.008)}{.048}\ L_i - \underset{(.0023)}{.0028}\ S_i + \underset{(.040)}{.115}\ C_i, \tag{19}$$

where z_i''' is omitted. About 70 per cent[48] of the variation among firms in the intrafirm rate of diffusion can be explained by the regression. Thus the model, simple and incomplete though it is, seems quite useful.[49]

[46] Actually, the analysis is carried out with another measure of the rate of diffusion, not Q_i. But using the theoretical relationship between this measure and Q_i, Equation 18 follows.

[47] These estimates were derived from correspondence with the firms. Each firm was asked to estimate the average payout period for the diesel locomotives it bought during 1946–57. The reciprocal of this payout period, which is a crude estimate of the rate of return, was used as an estimate of ρ_i.

[48] Strictly speaking, this percentage refers to the explained variation in the measure referred to in note 46, not to Q_i. See Mansfield, "Intrafirm Rates of Diffusion."

[49] Estimates were made of the effects on the intrafirm rate of diffusion (using both ownership and utilization data) of other variables besides ρ_i, L_i, S_i, and C_i. Specifically, I estimated the effect of: (1) the age distribution of the steam locomotives owned by the i^{th} firm when it "began" to dieselize; (2) the absolute number of diesel locomotives that the i^{th} firm had to acquire in order to go from 10 to 90 per cent of full dieselization; (3) the average length of haul of the i^{th} firm; and (4) the profitability of the i^{th} firm. With use of ownership data, the effect of none of these variables was significant. With use of utilization data, the age distribution of the steam locomotives had a significant effect, but the other variables did not.

VIII. Recent and Prospective Changes in Railroad Technology

In previous sections, I described measurements of the rate of technical change and presented theoretical and empirical results regarding the underlying processes of invention, innovation, and diffusion in the railroad industry, but little attention was paid to the specific improvements that have occurred recently in railroad technology. This section tries to fill the gap. It presents a brief list of the more important innovations that have come into limited or general use since World War II, and the innovations on the horizon that presidents of twenty-four Class I railroads regarded as potentially most important.[50]

First, consider the improvements in locomotives. During the postwar period almost all the nation's steam locomotives have been replaced by the vastly more economical diesel locomotive. Moreover, the diesel locomotive has been improved in a number of important ways. Tractive effort and horsepower have been increased, cooling systems have been improved, and electric circuits have been modified. In addition, experiments have been carried out by the Southern Pacific and the Denver and Rio Grande Western with diesel-hydraulic locomotives, which have proved useful in Europe.[51]

Second, consider the improvements in rolling stock, which has progressively increased in capacity and suitability for specific needs. Important developments in this area have been the three-tier, rack-type car for transporting autos, the mechanically refrigerated car, cars equipped with various shock-absorbing and lading-protection devices, cars using lubricating pads instead of oil-soaked waste packing, and hot box detectors. In addition, there has been the enormously successful use of piggybacking.

Third, consider the many applications of electronics to railroad operations. Whereas there was practically no use of radio immediately after World War II, it now is used between railroad offices, stations, moving trains, crews of different trains, and crews on the locomotive and caboose of the same train. In addition, over 8,000 miles of

[50] These lists were obtained by asking the presidents of thirty Class I railroads to list (1) the changes in railroad technology occurring since World War II they considered most important, and (2) the innovations likely to be introduced in the next decade and considered to be of considerable importance to the industry. Replies were received from twenty-four, or 80 per cent of the railroad presidents.

[51] On the diesel-hydraulic locomotive, see R. McBrian, "New Motive Power Technology," *Technological Change and the Future of the Railways*, Evanston, 1961.

microwave are now in service in the United States and Canada;[52] and electronic data processing equipment now is used in the area of accounting, payrolls, inventory and ordering work, car tracing and distribution, and equipment maintenance. Moreover, computers have made possible the application of various newly developed operations research techniques.[53] Centralized traffic control, first employed in the twenties, has been improved and its use has spread to over 31,000 miles of railroad. The automatic and semiautomatic classification yards, about forty of which are in operation in the United States, materially improved service and reduced operating costs.

Fourth, consider the improvements in track construction and maintenance. Probably the most important of these is the mechanization of maintenance of way, which has enabled the railroads to do with fifteen men what formerly required sixty.[54] In addition, there is the welding of rail sections to form continuous lengths of 1,000 feet or more, electronic and supersonic methods of testing rails, and improved techniques for preserving crossties.

Finally, considering innovations in railroad technology that are on the horizon (i.e., those likely to be introduced in the next decade), which, if any, are likely to be of considerable importance to the industry over the next few decades? In reply to this question, twenty-four presidents of Class I railroads gave the following answers. First, most of them listed the automated, crewless train, which is already being used in a limited way on local operations. Second, many listed new types of locomotives—the diesel hydraulic, locomotives powered by commercial electricity and eventually, perhaps, by nuclear power. Third, many listed the integral train; use of computers for simulation, train dispatching, etc.; automated freight car identification; and further containerization.

IX. Technical Change, Investment, and Prospective Employment

Supposing technical change in the railroad industry continues at its 1917–59 rate and that the industry's structure and work rules remain

[52] D. J. Russell, "United States Railroads: Developments, Problems and Opportunities," address before the International Railway Congress, June 22, 1962.

[53] E.g., E. Mansfield and H. Wein, "A Model for the Location of Railroad Classification Yard," *Management Science*, Apr. 1958; *idem*, "Linear Decision Rules and Freight Yard Operations," *Journal of Industrial Engineering*, Mar.–Apr. 1958; *idem*, "A Regression Control Chart for Costs," *Applied Statistics*, Mar. 1958; M. Beckmann, C. McGuire and C. Winsten, *Studies in the Economics of Transportation*, New Haven, 1956.

[54] These figures come from correspondence with the president of a major eastern road.

fixed, what will be the level of railroad employment by 1972? To help answer this question, we assume that the model in equations 1 and 2 held in the railroad industry during the past and that it continues to hold during 1960–72. Let us also assume that the estimates of λ, α, and δ derived in Section III are correct and will continue to be correct during 1960–72. If so, it follows that

$$\tilde{Q} = e^{-63.4}\tilde{L}^{.86}\left[\sum_{t=1840}^{1959} e^{.232t}I(t) + \tilde{I}\sum_{t=1960}^{1972} e^{.232t}\right]^{.14}, \tag{20}$$

where $\tilde{Q}$ is the output of the railroad industry in 1972 (1929 = 100), $\tilde{L}$ is the total man-hours employed by the industry in 1972 (1929 = 100), and $\tilde{I}$ is the annual gross investment (in millions of 1929 dollars).[55] Thus,

$$\ln \tilde{L} = .86^{-1}\left\{\ln \tilde{Q} + 63.4 - .14 \ln \left[\sum_{t=1840}^{1959} e^{.232t}I(t) + \tilde{I}\sum_{t=1960}^{1972} e^{.232t}\right]\right\}. \tag{21}$$

Using Equation 21 together with estimates of $\tilde{Q}$ and $\tilde{I}$, one can obtain conditional forecasts of $\tilde{L}$. Table 3 shows the values of $\tilde{L}$ associated with various levels of $\tilde{Q}$ and $\tilde{I}$.

What are reasonable estimates of $\tilde{Q}$ and $\tilde{I}$? According to forecasts made for this purpose by presidents of fourteen Class I railroads, $\tilde{Q}$ is likely to be about 144.[56] (These forecasts were expressed in terms of percentage increases over 1962, and the average forecast was a 19 per cent increase, the standard deviation being 9 percentage points.) With regard to $\tilde{I}$, use of 400 does not seem unreasonable; it is the average value of $I(t)$ during the late fifties (1954–59). Of course, these are only informed guesses, but what do they imply about $\tilde{L}$? To judge from Table 3, they imply that railroad employment in 1972 will be 35.7 per cent of its 1929 level, or 7 per cent less than its 1962 level.

How does this result compare with other sorts of forecast? According to forecasts made by the railroad presidents, employment in 1972 will be about 5 per cent below its 1962 level. (This is the average of their forecasts, and the standard deviation about this average was 12 percentage points.) Thus, their average forecast is not too different from

[55] I assume in Equation 19 that pre-1840 investment can be neglected and that gross investment can be assumed to occur at a constant rate during 1960–72. Moreover, rough estimates of $I(t)$ must be used for 1840–70, since Ulmer's figures go back only to 1870. Also, 5-year moving averages of $I(t)$ are used for 1870–1910 rather than the data for individual years used in previous sections of the paper. This should make little difference.

[56] These forecasts, like those described in the following paragraph in the text, were obtained from correspondence with the firms. The 1962 values of Q and L are estimates based on preliminary data.

TABLE 3

CONDITIONAL FORECASTS OF 1972 RAILROAD EMPLOYMENT, GIVEN 1972 RAILROAD OUTPUT AND AVERAGE ANNUAL GROSS INVESTMENT DURING 1962-72

Annual Investment (millions of 1929 dollars)	1972 Output					
	110	120	130	140	150	160
	1972 EMPLOYMENT (1929 = 100)					
400	26.1	28.8	31.7	34.5	37.4	40.3
600	24.5	27.1	29.7	32.4	35.1	37.8
800	23.4	25.9	28.4	31.0	33.6	36.2
	1972 EMPLOYMENT (1962 = 100)					
400	68	75	83	90	97	105
600	64	71	77	84	91	98
800	61	67	74	81	88	94

Source: Equation (21).

ours. However, if one uses the relatively crude, but common, procedure of extrapolating output per man-hour and dividing it into $\tilde{Q}$, the resulting forecast is that railroad employment in 1972 will be about 40.4 per cent of the 1929 level, or 5 per cent above its 1962 level.[57] This is appreciably higher than our forecast.

In conclusion, on the basis of these estimates of $\tilde{Q}$ and $\tilde{I}$, the model indicates that railroad employment will be 7 per cent below its 1962 level, if technical change continues at its 1917–59 rate. Any forecast of this sort should be taken with a generous grain of salt. First, the estimates of $\tilde{Q}$ and $\tilde{I}$ may be wrong. These variables are influenced by changes in factor prices, prices of competing means of transportation, consumer tastes, income levels, conditions in the money market, policies of regulatory agencies, and a host of other factors. To forecast $\tilde{Q}$ and $\tilde{I}$ is almost as difficult as to forecast $\tilde{L}$ itself.

Second, the production function in Equation 2 is obviously only a first approximation. For example, since economies of scale are omitted, the potential effects of the much-publicized, proposed mergers on employment are excluded. These effects are likely to be important. Third, it is assumed implicitly that the ratio of the amount of labor

[57] Extrapolating the regression of the logarithm of railroad output per man-hour on time, the resulting estimate of 1972 output per man-hour is 359 (1929 = 100). Dividing this estimate into the forecast of $\tilde{Q}$, we obtain 40.4 as an estimate of $\tilde{L}$.

employed to the minimum amount required to produce the forecasted level of output will be close to the ratio of actual to required employment in the past. If this ratio were to decrease, because of changes in union or public policy, the results would obviously be affected. However, the required correction might not be difficult to make.[58]

X. Summary and Conclusion

My purpose in this paper has been to estimate the rate of technical change in the railroad industry and to investigate the underlying processes of invention, innovation, and diffusion responsible for important changes in railroad practices. The principal results are as follows:

1. During 1890–1953, output per man-hour rose more rapidly in the railroad industry than in the economy as a whole but less rapidly than in all transportation. Comparing periods of relatively full employment, output per man-hour in the railroad industry rose at a relatively steady rate during that period.

2. On the assumption that technical change was capital embodied and neutral and that the production function was Cobb-Douglas, the rate of technical change in the railroad industry, defined as a shift over time in the production function, was about 3.0 per cent per year. This compares with Solow's estimate of 2.5 per cent per year for the economy as a whole.

3. To judge from Schmookler's chronology of railroad patents and important railroad inventions, there was a tendency, during 1870–1950,

[58] It is often asserted that there is a considerable amount of featherbedding in the railroad industry. If essentially useless "make work" accounted for a relatively stable proportion of the total time put in each year by labor, $L(t)$, which is an index number, will not be affected appreciably whether it is based on actual employment or minimum necessary employment. So long as the labor time not devoted to make "work" was allocated optimally among vintages of capital, the estimates in Table 3—as well as the estimates of λ in Section III—are unaffected by the presence of "make work." But if the latter were to be eliminated or cut substantially, the estimates in Table 3 would obviously be too high. Given any set of assumptions about changes in work rules, it should be possible to make at least an approximate correction. For some relevant discussions, see *The Report of the Presidential Railroad Commission*, Washington, 1962; and M. Horowitz, *Manpower Utilization in the Railroad Industry*, Boston, 1960.

Note too that we do not distinguish among various kinds of labor in this section. For a description of recent changes in the relative importance of various occupations, see W. Haber and others, *Maintenance of Way Employment on U.S. Railroads*, Detroit, 1957; and E. Jakubauskas', "Technological Change and Recent Trends in the Composition of Railroad Employment," *Quarterly Review of Economics and Business*, Nov. 1962.

for the rate of occurrence of these inventions to decrease with time, such a tendency being in accord with the Kuznets, Burns, and Fabricant hypothesis. There was also a tendency, in accord with Schmookler's hypothesis, for the rate of invention to be directly related to the lagged rate of capital formation in the railroad industry.

4. On the basis of a small sample of the most important innovations occurring in the twentieth century, the largest railroads seemed to do a disproportionately large share of the innovating, disproportionate in terms of their share of the industry's ton-miles. In part, this can be explained by the capital requirements needed to innovate, the minimum size of firm required to use the innovations, and the size distribution of the potential users.

5. When a new technique is introduced by one railroad, several decades usually elapse before all the others begin using it. As in other industries, the rate of imitation seems to be directly related to the profitability of the innovation and inversely related to the size of the investment required to introduce it. However, holding these factors constant, the imitation process seems to go on at a somewhat slower pace in the railroad industry than in the other industries for which we have data.

6. Judging by the diesel locomotive, the rate at which a railroad, once it begins to use a new technique, substitutes it for older methods is directly related to the profitability of the investment in the new technique, the length of time the firm waited before beginning to use it, and the liquidity of the firm; but the rate of substitution is inversely related to the size of the firm.

7. Some of the most important developments since World War II have been replacement of steam locomotives by diesels, the extension of piggybacking, use of larger and special-purpose cars, application of electronic data processing, the spread of centralized traffic control, development of automatic classification yards, and mechanization of maintenance of way.

8. According to twenty-four railroad presidents, the innovations on the horizon that are likely to be most important during the next few decades are the automated, crewless train, the integral train, the diesel-hydraulic locomotive, locomotives powered by commercial electricity, automated freight car identification, further use of computers, and further containerization.

9. If the production function continues to shift at the 1917–59 rate and if the railroads continue to invest in new plant and equipment at the 1955–59 rate, one can estimate the industry's 1972 labor requirements on the basis of forecasts of 1972 railroad output. Assuming for

the calculation a 19 per cent increase in output, which was the average forecast made by the railroad presidents, the results suggest that railroad employment in 1972 will be about 7 per cent below its 1962 level. This is fairly close to the average forecast made by the railroad presidents—that 1972 employment will be 5 per cent below its 1962 level. Note, however, that this assumes that no important mergers or changes in work rules take place.

Besides promoting a better understanding of the processes of innovation and technical change in the railroad industry, these findings may be useful in connection with the formulation of public policy. They provide information about the technical progressiveness, or backwardness, of the railroad industry relative to other industries. They provide employment forecasts which, despite their roughness, should be useful in indicating the extent of the future unemployment problem in the industry. They compare some aspects of the technological performance of large and small railroads, a relevant consideration in estimating the effect of the proposed railroad mergers on technical progress in the industry.

In conclusion, the limitations of these results should be emphasized. The model used in Sections III and IX is obviously only a crude first approximation. The data in Section IV have obvious weaknesses. The results in Sections V to VII are based on only a few innovations, which may not be entirely representative. Nonetheless, the findings should be helpful, if used with caution, to transportation economists and economists concerned with the processes of innovation and technical change.