

COWLES FOUNDATION FOR RESEARCH IN ECONOMICS

AT YALE UNIVERSITY

Box 2125, Yale Station  
New Haven, Connecticut

COWLES FOUNDATION DISCUSSION PAPER NO. 134 (REVISED)

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The Speed of Response of Firms to New Techniques

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May 25, 1962

# The Speed of Response of Firms to New Techniques<sup>\*</sup>

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## 1. Introduction

Economists have long been interested in the process whereby new techniques spread from firm to firm; but until recently our knowledge of its workings did not extend far beyond Schumpeter's simple assertion that once a firm introduces a successful innovation, a host of imitators appear on the scene. In the past few years, considerable progress has been made in investigating some important aspects of this imitation process. It is unfortunate that other important aspects are still largely unexplored.

Specifically, although it has often been observed that some firms begin using a new technique long before other firms do, there have been very few studies of the factors responsible for these differences.<sup>1/</sup> Can we construct models to help predict whether one firm will be quicker than another? What are the quantitative effects of various factors on a firm's speed of response? In addition, we lack information regarding the extent to which technical leadership of this sort is concentrated in the hands of a few firms. Do the same members of an industry tend to be relatively quick to introduce various new techniques, or are the leaders in one case likely to be the followers in another?

The purpose of this paper is to help answer these questions. First, hypotheses are presented regarding the effects of various factors on the length of time a firm waits before using a particular technique. Second, using data describing the diffusion of fourteen major innovations, we test these hypotheses and estimate the effects of these factors on a firm's speed of response. Third, using the same data, we estimate the extent to which leadership of this sort in four important industries has been concentrated in the hands of a relatively few firms.

The plan of the paper is as follows. Sections 2 - 4 take up the effects of a firm's size and the profitability of the investment in the innovation on its speed of response. Sections 5 - 6 deal with the effects of a firm's growth rate, past profits, liquidity position, and other such factors. Section 7 measures the extent to which leadership of this kind was concentrated among a relatively few firms in the bituminous coal, railroad, brewing, and iron and steel industries. Section 8 summarizes the results and provides some concluding remarks.

## 2. Size of Firm and the Profitability of its Investment in the Innovation

This section presents four propositions regarding the effects of a firm's size and the extent of the returns it can obtain from the innovation on how long it waits before introducing the innovation. If they hold, these propositions should provide a basis for predicting whether one firm will be

quicker than another to use an innovation. Section 3 converts these general propositions into testable hypotheses, and Section 4 carries out the appropriate tests.

The first proposition states that, other things held equal, the length of time a firm waits before using a new technique tends to be inversely related to its size.<sup>2/</sup> There are at least three reasons for believing that this is so. First, the costs and risks involved in being among the first to use a new technique are likely to loom much larger for small firms than for big ones. Because of their larger financial resources, bigger engineering departments, better facilities for experimentation, and closer ties with equipment manufacturers, bigger firms can play the role of the pioneer more cheaply and with less risk than smaller ones can.

Second, large firms, because they encompass a wider range of operating conditions, have a better chance of containing those conditions for which the innovation is applicable at first. This is important because, when an innovation first appears, its application is often restricted to certain operating conditions, and improvements occur later that extend its usefulness. Third, because they have more units of any particular type of equipment, large firms are more likely at any point in time to have some units that will soon have to be replaced. Thus, if an innovation occurs that is designed to replace this type of equipment, they probably can begin using it more quickly than smaller firms.<sup>3/</sup>

The second proposition elaborates on the first. It states that, as a firm's size increases, the length of time it waits tends to decrease at an

increasing rate. This proposition stems from the following model. Suppose that a new type of equipment is put on the market and that the  $j^{\text{th}}$  firm will eventually own  $\alpha_j$  units of this equipment. Suppose that  $x_{ij}$ , the length of time that elapses (from the date when the innovation is first put on the market) before the  $j^{\text{th}}$  firm's  $i^{\text{th}}$  unit ( $i = 1, \dots, \alpha_j$ ) is installed is a random variable with cumulative distribution function,  $F(x)$ , and that the time elapsing before one of its units is installed is independent of that for another unit.<sup>4/</sup>

Under these highly simplified circumstances, the expected length of time a firm with an eventual complement of  $\alpha$  units will wait before beginning to use the innovation is

$$(1) \quad E(\alpha) = \alpha \int_0^M x [1 - F(x)]^{\alpha-1} F'(x) dx ,$$

where  $M$  is the maximum value of  $x_{ij}$ . Integrating by parts, we have

$$(2) \quad E(\alpha) = \int_0^M [1 - F(x)]^{\alpha} dx ,$$

and it is easy to show that

$$(3) \quad E(\alpha) - E(\alpha + 1) = \int_0^M [1 - F(x)]^{\alpha} F(x) dx > 0 ,$$

$$(4) \quad [E(\alpha) - E(\alpha+1)] - [E(\alpha+1) - E(\alpha+2)] = \int_0^M [1-F(x)]^{\alpha} F^2(x) dx > 0 .$$

Thus, if  $\alpha_j$  is proportional to the  $j^{\text{th}}$  firm's size (measured in terms of sales or production), the expected length of time a firm waits should decrease at an increasing rate with increases in its size.<sup>5/</sup>

The third proposition states that, other factors held equal, the length of time a firm waits tends to be inversely related to the extent of the returns it obtains from the innovation. If these returns are very high, the expected returns are likely to be high enough to make the gamble involved in introducing the innovation seem worthwhile at the outset. If they are not so high, the firm will wait until the risks are reduced to the point where the investment seems warranted.<sup>6/</sup>

Finally, the fourth proposition states that, as the profitability of a firm's investment in the innovation increases, the length of time the firm waits decreases at an increasing rate. Certainly, it seems plausible that an increase of one percentage point in the rate of return from the investment in the innovation will have a progressively smaller effect on the firm's rate of response, as the investment becomes more and more profitable.

### 3. Model and Data

To permit testing, we translate these propositions into the following, more specific model:

$$(5) \quad d_{ij} = Q_{i1} H_{ij}^{a_{i2}} S_{ij}^{a_3} e^{\epsilon_{ij}},$$

where  $d_{ij}$  is the number of years the  $j^{\text{th}}$  firm waits before beginning to use the  $i^{\text{th}}$  innovation,  $S_{ij}$  is its size,  $H_{ij}$  is a measure of the profitability of its investment in the innovation,  $\epsilon_{ij}$  is a random error term, and both  $a_{12}$  and  $a_3$  are negative.

This functional form, although arbitrary in many respects, seems quite reasonable. It is in accord with the propositions in the previous section stating that, as  $S_{ij}$  and  $H_{ij}$  increase,  $E(d_{ij})$  decreases at an increasing rate. Moreover, a multiplicative relationship makes sense here since the effect on  $d_{ij}$  of each of the exogenous variables is likely to depend on the level of the other. For example, differences in firm size would be expected to have less effect if an innovation is extremely profitable than if it is less so. Similarly, differences in the profitability of the investment in the innovation would be expected to have less effect if a firm is large than if it is small. <sup>7/</sup>

To test the propositions in the previous section and to estimate the effects on  $d_{ij}$  of  $S_{ij}$  and  $H_{ij}$ , we estimated  $a_{12}$  and  $a_3$  for a number of innovations, assuming that the latter were in some sense representative. In particular, data were collected regarding the diffusion of fourteen innovations in the bituminous coal, iron and steel, brewing, and railroad industries: the shuttle car, trackless mobile loader, and continuous mining machine (in bituminous coal); the by-product coke oven, continuous wide strip mill, and continuous annealing (in iron and steel); the pallet-loading machine, tin container, and high-speed bottle filler (in brewing); and the diesel locomotive, centralized traffic control, mikado locomotive, trailing-truck locomotive, and car retarders.

(in railroads).<sup>8/</sup>

Three kinds of data were collected in each case. First, we obtained the date when each major firm in the industry began to use the innovation, and we subtracted it from the date when the first firm began to use it to obtain  $d_{ij}$ .<sup>9/</sup> Second, an estimate was made of each firm's size. Physical output was used in the coal and brewing industries, ingot capacity was used in steel, and freight ton-miles were used in the railroad industry to measure  $S_{ij}$ .<sup>10/</sup>

Third, because it was impossible to get a direct estimate of the innovation's profitability to each firm, surrogates were obtained where possible. For example, since the profitability of a firm's investment in a continuous mining machine was likely to vary directly with the percent of its output derived from "high seams," this percentage was used as a surrogate. Other surrogates were the reciprocal of the percent of a railroad's mileage that was double track (centralized traffic control), the reciprocal of the percent of a firm's revenues derived from hauling coal (diesel locomotive), the ratio of a firm's rolling capacity to its ingot capacity (continuous wide strip mill), and a firm's tinplate capacity as a percent of its ingot capacity (continuous annealing). Despite considerable effort, no suitable surrogates could be found for the remaining nine innovations, and the surrogates used in these five cases are obviously very rough.<sup>11/</sup>



Finally, assuming that the surrogate was proportional to  $H_{ij}$  in each case, it follows that

$$(5') \quad \ln d_{ij} = a_{i1} + a_{i2} \ln P_{ij} + a_3 \ln S_j + \epsilon_{ij} .$$

(Of course, it is not necessary to assume that the ratio of the surrogate to  $H_{ij}$  was the same for each innovation.) Using equation (5'), one can easily obtain least square estimates of the  $a$ 's in those cases where data on both  $S_{ij}$  and  $P_{ij}$  are available. Where data are available for  $S_{ij}$  only, it is necessary to omit the second term on the right hand side of equation (5'). Thus, two regressions are run, one including observations where data for both  $S_{ij}$  and  $P_{ij}$  are available and the other including observations where only data for  $S_{ij}$  are available.<sup>12/</sup>

#### 4. Empirical Results

Using these rather crude data and techniques, we obtained estimates of  $a_{i1}$ ,  $a_3$ , and (where possible)  $a_{i2}$ . The results, based on 127 (data for both  $S_{ij}$  and  $P_{ij}$ ) and 167 (data for  $S_{ij}$  only) observations, are shown in Tables 1 - 3.<sup>13/</sup> In examining the results, somewhat more weight must be given to the estimates based on data for both  $S_{ij}$  and  $P_{ij}$ , since the other estimates are more likely to be biased and they only provide evidence regarding some, not all, of the hypotheses in Section 2.

TABLE 1

Estimates of the Effects of a Firm's Size, Growth Rate, Past Profits, Age of President, Liquidity, and Profit Trend on Its Delay in Introducing a New Technique, Fourteen Innovations, Coal, Steel, Brewing and Railroad Industries.

<u>Parameter<sup>1/</sup></u>	<u>Innovations with data on <math>P_{ij}</math></u>	<u>Innovations without data on <math>P_{ij}</math></u>
Size of firm: <sup>2/</sup>		
$a_3$	- .40* (.06)	- .32* (.12)
$b_3$	- .41* (.07)	- .80* (.28)
$c_3$	- .82* (.26)	- .83* (.29)
$\theta_3$	- .42* (.08)	--
Growth rate: <sup>3/</sup>		
$b_4$	- .11 (.18)	.69 (.36)
$c_4$	- .23 (.29)	.59 (.36)
$\theta_4$	- .08 (.19)	--
Past Profits: <sup>3/</sup>		
$b_5$	1.80 (2.68)	.01 (4.84)
$c_5$	6.30 (6.68)	- 1.10 (5.38)
$\theta_5$	.68 (3.07)	--
Age of president: <sup>4/</sup>		
$c_6$	- 1.12 (1.50)	2.44 (1.51)

TABLE 1 (Continued)

<u>Parameter</u> <sup>1/</sup>	<u>Innovations with data on <math>P_{ij}</math></u>	<u>Innovations without data on <math>P_{ij}</math></u>
Liquidity <sup>4/</sup>		
$\theta_6$	.18 (.17)	--
Profit trend <sup>4/</sup>		
$\theta_7$	.21 (.20)	--

Source: See notes 9-11.

1/ For definitions of these parameters, see Section 3 (for the a's), 5 (for the b's), and 6 (for the c's and  $\theta$ 's).

2/ The units in which a firm's size is measured here are billions of freight ton-miles (railroad innovations), thousands of tons of capacity (strip mill and coke oven), dollars of sales (annealing), production in barrels (brewing innovations), production in tons (shuttle car and mobile loader), and millions of tons produced (continuous mining machine).

3/ For the units in which these variables are measured, see Section 5. ( $\Pi_{ij}$  is measured in percentage points.)

4/ For the units in which these variables are measured, see Section 6. ( $A_{ij}$  is measured in years.)

\* Statistically significant at .05 probability level.

TABLE 2

Estimates of the Effects of the Profitability of a Firm's Investment in an Innovation on Its Delay in Introducing the Innovation, Five Innovations, Coal, Steel, and Railroad Industries

<u>Innovation</u>	Parameter <sup>1/</sup>			
	<u>a<sub>12</sub></u>	<u>b<sub>12</sub></u>	<u>c<sub>12</sub></u>	<u>θ<sub>12</sub></u>
Diesel locomotive	- .03 (.09)	- .02 (.11)	--	.00 (.11)
Continuous mining machine	- .28 (.60)	- .67 (1.75)	- 1.75 ( 2.13)	- .31 (1.81)
Continuous wide strip mill	- .89* (.25)	- .85* (.29)	- 1.25* (.38)	--
Continuous annealing	-1.53* (.33)	-1.55* (.35)	- 1.87* (.42)	-1.29* (.42)
Centralized traffic control	- .05 (.31)	- .02 (.34)	.16 (.35)	- .23 (.28)

Source: See notes 9-10.

<sup>1/</sup> For definitions of these parameters, see Section 3 (for a<sub>12</sub>), 5 (for b<sub>12</sub>), and 6 (for c<sub>12</sub> and θ<sub>12</sub>). Section 3 describes the units in which the surrogates for the profitability of a firm's investment in the innovation are measured.

\* Statistically significant at .05 probability level.

TABLE 3

Estimates of  $a_{i1}$ ,  $b_{i1}$ ,  $c_{i1}$ , and  $\theta_{i1}$ , Fourteen Innovations,  
Coal, Steel, Brewing, and Railroad Industries.<sup>1/</sup>

<u>Innovation</u>	<u><math>a_{i1}</math></u>	<u><math>b_{i1}</math></u>	<u><math>c_{i1}</math></u>	<u><math>\theta_{i1}</math></u>
Data on $P_{ij}$ Available:				
Diesel locomotive	2.58	3.17	--	2.79
Continuous mining machine	3.02	4.84	14.82	2.83
Continuous wide strip mill	7.38	7.70	16.67	--
Continuous annealing	12.77	13.46	26.70	12.46
Centralized traffic control	2.98	3.62	10.04	2.67
Data on $P_{ij}$ Unavailable:				
Shuttle Car	5.56	8.46	- .11	--
Trackless mobile loader	6.11	9.92	1.43	--
Tin container	6.35	--	--	--
Pallet loading machine	5.96	9.13	.15	--
High speed bottle filler	6.17	9.54	--	--
By-product coke oven	4.29	--	--	--
Trailing-truck locomotive	2.34	-.42	-9.56	--
Car retarders	2.66	- .18	-9.30	--
Mikado locomotive	2.76	--	--	--

Source: See notes 9-11.

<sup>1/</sup> For definitions of these parameters, see Section 3 (for  $a_{i1}$ ),  
5 (for  $b_{i1}$ ), and 6 (for  $c_{i1}$  and  $\theta_{i1}$ ).

The estimates in Tables 1 and 2 provide considerable support for these hypotheses. Both in the cases where data for  $S_{ij}$  and  $P_{ij}$  are available and in the cases where only data on  $S_{ij}$  are available, the estimate of  $a_3$  has the proper sign and is statistically significant. Moreover, the two independent estimates of  $a_3$  in Table 1 are surprisingly close. Apparently, the elasticity of delay with respect to firm size is about  $-.4$ . That is,

$$\frac{dd_{ij}}{dS_{ij}} \frac{S_{ij}}{d_{ij}} \doteq -.4 .$$

The estimates of  $a_{12}$  are also quite consistent with the hypotheses presented above. In every case, these estimates have the expected sign, although they often are statistically non-significant.<sup>14/</sup> As one would expect, there seems to be considerable variation among innovations in  $a_{12}$ , the estimated elasticity of delay with respect to the profitability of a firm's investment in the innovation ranging from  $-.03$  (diesel locomotive) to  $-1.53$  (continuous annealing). That is,  $\frac{dd_{ij}}{dH_{ij}} \frac{H_{ij}}{d_{ij}}$  ranges from  $-.03$  to  $-1.53$ .

In addition, there is evidence of another sort that seems to support these findings. When about thirty executives in these industries were interviewed, their impression seemed to be that these hypotheses usually held in their industries.<sup>15/</sup> However, there were some interindustry differences in their impression of the effect of a firm's size. In the coal, brewing, and

railroad industries, their almost unanimous impression was that the smaller firms were slower than the large ones to install important new techniques, but in the steel industry many believed the opposite to be true.<sup>16/</sup>

Of course, all of this measures the effects of  $S_{ij}$  and  $P_{ij}$  on the average value of  $d_{ij}$ . Although these effects may be substantial, the model may nonetheless be of little use for predictive purposes because of large residual variation. (Cf. notes 17 and 18.) What is the probability that a prediction based on these hypotheses would have held in these cases? Suppose that one firm was  $X$  times as large as another, the value of  $P_{ij}$  being the same for each firm, and that we predicted that the larger firm would be quicker than the smaller one to introduce the innovation. What would have been our chances of being correct?

Of course, the answer depends on how large  $X$  was. If  $X = 4$ , our chances of being correct were about .80, whereas if  $X = 2$ , our chances were only about .65. (To obtain these figures, we assume that  $\epsilon_{ij}$  was normally distributed with variance  $\sigma_e^2$ . If so, our chances of being right were  $U[-\alpha_3 \ln X / \sigma_e / \sqrt{2}]$ , where  $U$  is the unit normal cumulative distribution function. Estimates  $\alpha_3$  and  $\sigma_e$  were inserted in this expression to obtain the figures given above.<sup>17/</sup>)

Thus, so long as the difference between firm sizes is quite large, it appears that predictions of this sort would have had a very good chance of being correct. Moreover, although the situation is somewhat more

complicated in cases where predictions are based on differences in values of  $P_{ij}$  ( $S_{ij}$  being held constant), the results suggest that these predictions would also have had a very good chance of being right if the difference in  $P_{ij}$  was large. For example, if the investment in a continuous wide strip mill was four times as profitable for one firm as another, the probability was about .95 that the former firm was quicker than the latter to begin using it.<sup>18/</sup>

In conclusion, three additional points should be made regarding the empirical results. First, the results are consistent with the hypotheses that  $a_{12}$  depends on the average profitability of the innovation and on the size of the investment required to install it. This would be expected on the basis of the findings of a related paper [13].<sup>19/</sup> Second, the results show that a considerable amount of the variation in  $\ln d_{ij}$  can be explained by  $\ln S_{ij}$  and  $\ln P_{ij}$ . For those cases where data for both  $S_{ij}$  and  $P_{ij}$  are available, almost half of the variation can be explained by these variables.<sup>20/</sup> Third, if one does not constrain  $a_3$  to be the same for all innovations, the results indicate that (with only one exception)  $d_{ij}$  is inversely related to  $S_{ij}$  and  $P_{ij}$  in the case of each innovation taken separately.<sup>21/</sup>



5. Growth Rate and Profitability of the Firm

Besides a firm's size and the extent of the returns it obtains from the innovation, there are many other factors that may influence its speed of response to an innovation. Sections 5-6 present and test propositions regarding the effects of five such factors. If one could be reasonably sure that these propositions would hold, they could be useful -- in the same way as the propositions in Section 2 -- in predicting whether one firm would be quicker than another to use an innovation.

The first proposition states that, other factors held equal, the length of time a firm waits before introducing a new technique tends to be inversely related to its rate of growth. If a firm is expanding at a relatively rapid rate, it might be expected to install a new technique relatively quickly because it can introduce it in its new plants, whereas a firm experiencing little or no growth must wait until it can profitably replace existing equipment. Of course, the significance of this factor will vary somewhat, but for a large class of innovations, it would seem to be important.<sup>22/</sup>

The second proposition states that, other factors held equal, the length of time a firm waits before introducing a new technique tends to be inversely related to the firm's profitability. One would suppose that less profitable firms -- with their smaller cash inflows and poorer credit ratings -- would have more difficulty in financing the necessary investment and that they would be in a poorer position to take whatever risks are involved in being among the first to use it.<sup>23/</sup>

Assuming that these propositions (as well as those in Section 2) hold, we have

$$(6) \quad \ln d_{ij} = b_{11} + b_{12} \ln P_{ij} + b_3 \ln S_{ij} + b_4 \ln g_{ij} + b_5 \ln \Pi_{ij} + \epsilon'_{ij},$$

where  $\Pi_{ij}$  is the  $j^{\text{th}}$  firm's profits as a percent of its net worth during a three-year period soon after the innovation was first put on the market,  $g_{ij}$  is the percentage increase in the  $j^{\text{th}}$  firm's production or capacity (plus 100) during the (approximate) period during which the imitation process was going on, and  $\epsilon'_j$  is an error term.<sup>24/</sup> According to these propositions,  $b_{12}$ ,  $b_3$ ,  $b_4$ , and  $b_5$  should be negative.

To test each of these hypotheses, we estimate the b's, using all the innovations for which the necessary data on  $g_{ij}$  and  $\Pi_{ij}$  could be obtained from trade sources and Moody's for a reasonable number of firms. The resulting least-squares estimates in Tables 1-3, based on 115 (data for  $P_{ij}$ ) and 74 (no data for  $P_{ij}$ ) observations, provide no strong evidence in support of these hypotheses.<sup>25/</sup> Again, two regressions are run, one for observations where data could be obtained on  $P_{ij}$  and one for the rest. Both estimates of  $b_5$  and one estimate of  $b_4$  have the "wrong" sign. None of the estimates is statistically significant.

6. Age of President, Liquidity, and Profit Trend

Of course, if these hypotheses really hold, the inclusion of other independent variables in equation (6) may make it more apparent. As an experiment, we included  $A_{ij}$  -- the age of the  $j^{\text{th}}$  firm's president -- as an additional independent variable. It is often asserted that younger managements, being less bound by traditional ways, are more likely than older ones to introduce a new technique relatively quickly. Moreover, in agriculture, there is some evidence that this is the case [3, 9]. Assuming that this proposition (as well as the previous ones) holds, we have

$$(7) \quad \ln d_{ij} = c_{11} + c_{12} \ln P_{ij} + c_3 \ln S_{ij} + c_4 \ln \xi_{ij} + c_5 \ln \Pi_{ij} \\ + c_6 \ln A_{ij} + \epsilon_{ij}'' ,$$

where  $c_{12}, \dots, c_5$  are negative;  $c_6$  is positive; and  $\epsilon_j''$  is a random error term.

To test this hypothesis, we estimate the  $c$ 's using those innovations for which data regarding the exogenous variables could be obtained for a reasonable number of firms. Again, two regressions were run, one for observations where  $P_{ij}$  could be estimated and one for the rest. The results, based on 50 (data for  $P_{ij}$ ) and 68 (no data for  $P_{ij}$ ) observations, are shown in Tables 1-3. They provide no real evidence that  $\xi_{ij}$ ,  $\Pi_{ij}$ , or  $A_{ij}$  had a significant influence on  $d_{ij}$ ; half of the estimates of  $c_4$ ,  $c_5$ , and  $c_6$  have the "wrong" sign and none are statistically significant. 26/

Finally, we take a somewhat less detailed look at the effects of two other factors -- a firm's liquidity and its profit trend. With regard to liquidity, one might expect that more liquid firms would be better able to finance the investment in the innovation and that consequently they might be quicker than less liquid firms to use it. With regard to a firm's profit trend, one might suppose that firms with decreasing profits would be stimulated to search more diligently than other firms for new alternatives [17] and that, other things equal, they might tend to be quicker than others to begin using a new technique.

If these propositions (and those in Sections 2 and 5) hold for a given innovation, we have

$$(8) \quad \ln d_{ij} = \Theta_{11} + \Theta_{12} \ln P_{ij} + \Theta_3 \ln S_{ij} + \Theta_4 \ln \varepsilon_{ij} + \Theta_5 \ln \Pi_{ij} \\ + \Theta_6 \ln L_{ij} + \Theta_7 \ln t_{ij} + \varepsilon_{ij}^{\prime\prime},$$

where  $L_{ij}$  is the average value of the  $j^{\text{th}}$  firm's current ratio (current assets divided by current liabilities) during the three years up to and including the year when the innovation was first used in this country;  $t_{ij}$  is the slope of the linear regression of the  $j^{\text{th}}$  firm's profit rate against time (measured in years) during a six-year period just before the innovation was first used in this country;  $\Theta_{12}, \dots, \Theta_6$  are negative;  $\Theta_7$  is positive; and  $\varepsilon_{ij}^{\prime\prime}$  is an error term.

To test these hypotheses, we estimated the  $\Theta$ 's, using all innovations for which data regarding all of the exogenous variables could be obtained for a reasonable number of firms. The results, based on a single regression utilizing 101 observations, are shown in Tables 1 - 3. Half of the estimates of  $\Theta_4, \dots, \Theta_7$  have the "wrong" sign, and none are statistically significant.<sup>27/</sup>

In conclusion, there is no real evidence that any of the hypotheses in Sections 5 - 6 are of use in predicting whether one firm will be quicker than another to introduce a new technique. Judging from Tables 1 - 3, one cannot be at all sure (if  $S_{ij}$  and  $P_{ij}$  are held constant) that a more profitable firm will be quicker than a less profitable one, that a faster growing firm will be quicker than a slower growing one, that a more liquid firm will be quicker than a less liquid one, that a firm with a younger president will be quicker than one with an older president or that a firm with a downward profit trend will be quicker than one with an upward one. The effects of most of these factors are in the "wrong" direction and, without exception, they are statistically nonsignificant.<sup>28/</sup>

## 7. Concentration of Technical Leadership

To what extent do the firms that are quick -- or slow -- to introduce one innovation tend to be quick -- or slow -- to introduce others as well? How high is the correlation between how rapidly a firm introduces one innovation and how rapidly it introduces another? The answer to this question is important because it shows the extent to which technical leadership is concentrated in the hands of only a few members of an industry. In this section, we see how closely it has been concentrated among firms in the bituminous coal, railroad, brewing, and iron and steel industries.

As a first step, we note that the coefficient of correlation between how rapidly a firm introduces one innovation and how rapidly it introduces another is likely to be inversely related to the time interval separating the date when the one innovation first appeared from the date when the other innovation first appeared. Put differently, as the time interval separating the appearance of two innovations increases, there is likely to be less tendency for the same firms to be relatively quick -- or slow -- to introduce both. This seems reasonable because, as time goes on, technical leadership, if at all polarized, is likely to pass from one group of firms to another.<sup>29/</sup>

Assuming that this hypothesis is correct and that a linear function is satisfactory, we have

$$(9) \quad \rho_{qr} = v + w t_{qr} + Z_{qr} ,$$

where  $\rho_{qr}$  is the coefficient of correlation between the length of time a firm waits before introducing the  $q^{\text{th}}$  innovation and the length of time it waits before introducing the  $r^{\text{th}}$  innovation,  $t_{qr}$  is the interval (in years) between the dates when these two innovations were first used commercially, and  $Z_{qr}$  is a random error term.<sup>30/</sup>

Estimates of  $v$  and  $w$  for each industry would allow us to estimate the average correlation coefficient, given that  $t_{qr}$  is fixed. To obtain estimates of  $v$  and  $w$ , we estimated  $\rho_{qr}$  for each pair of innovations in a given industry (Table 4). Then, since the appropriate analysis of covariance provides no evidence to the contrary,<sup>31/</sup> we assumed that there were no inter-industry differences in  $w$ ; and using least-squares, we found that

$$(10) \quad \rho_{qr} = \left\{ \begin{array}{c} .40 \\ .30 \\ .66 \\ .28 \end{array} \right\} - \frac{.012}{(.004)} t_{qr},$$

where  $Z_{qr}$  is omitted and the figures in brackets (reading from top to bottom) pertain to brewing, coal, steel, and railroads.

This result indicates at least four things. First, given that two innovations occur within a few decades of each other, one can expect some positive correlation between how long a firm waits before introducing one and how long it waits before introducing the other. Thus, if two innovations are reasonably close together in time, there is generally some tendency for the same firms to be relatively quick -- or slow -- to introduce both.<sup>32/</sup>

Table 4 -- Values of  $\rho_{qr}$  and  $t_{qr}$  for Nineteen Pairs of Innovations,  
Coal, Steel, Brewing, and Railroad Industries.<sup>1</sup>

<u>Pair of Innovations</u>	<u><math>\rho_{qr}</math></u>	<u><math>t_{qr}</math></u>	<u>Number of Firms</u>
Continuous mining machine: shuttle car	-.02	10	9
Continuous mining machine: trackless mobile loader	-.17	13	9
Shuttle car: trackless mobile loader	.54	3	11
By-product coke oven: continuous strip mill	.21	30	4
By-product coke oven: continuous annealing	.18	42	5
Continuous strip mill: continuous annealing	.53	12	7
High speed bottle filler: tin container <sup>2</sup>	.42	16	8
High speed bottle filler: pallet loading machine <sup>2</sup>	.24	3	8
Tin container: pallet loading machine	-.06	13	15
Centralized traffic control: trailing-truck locomotive	.02	2	21
Centralized traffic control: diesel locomotive	.04	2	23
Centralized traffic control: car retarders	.16	2	21
Centralized traffic control: mikado locomotive	.19	25	22
Trailing-truck locomotive: diesel locomotive	.26	0	22
Trailing-truck locomotive: car retarders	.32	0	20
Trailing-truck locomotive: mikado locomotive	.13	23	21
Diesel locomotive: car retarders	.41	0	22
Diesel locomotive: mikado locomotive	.12	23	23
Car retarders: mikado locomotive	-.29	23	21

Source: See Section 7.

<sup>1</sup>See Section 7 for definitions of  $\rho_{qr}$  and  $t_{qr}$ . The latter is measured in years. The number of firms in the final column differs from that used in previous sections. Only those firms for which we have data regarding both innovations could be included.

<sup>2</sup>Only firms already using high-speed bottle fillers are included here. See note 14.



Second, although there is some such tendency, technical leadership does not seem to be very highly concentrated in most of these industries. Even if two innovations occur simultaneously, the average value of  $\rho_{gr}$  in the bituminous coal, brewing, and railroad industries is only about .30; and if the innovations occur five years apart, it is only about .25. To see the implications of this, suppose that firms are ranked by how quickly they used a particular innovation and that one firm is one-quarter of the way down the ranking, whereas a second firm is three-quarters of the way down the ranking. If another innovation occurred five years later and  $\rho_{gr} = .25$ , the probability is only <sup>about</sup> .59 that the first firm would introduce it before the second firm.<sup>33/</sup>

Third, although leadership seems to be quite widely diffused in most of these industries, there is one exception -- iron and steel. If two innovations in steel occur close together in time, there seems to be a fairly high correlation (about .60) between how rapidly a firm introduces one and how rapidly it introduces the other. The higher correlation in steel may be due in part to a more unequal distribution among firms of research expenditures (and other such factors) than in other industries.<sup>34/</sup>

Fourth, as we expected, the estimate of  $w$  is negative and statistically significant. Thus, as the time interval separating two innovations increases, there is less correlation between a firm's speed of response to one and its speed of response to the other. But it is noteworthy that the correlation coefficient decreases very slowly, an increase in the time interval of one year resulting in a decrease of only about .01 in the correlation coefficient.

Finally, we should note that if the rank (not the product-moment) correlation coefficient had been used in equation (10), the results would have been almost exactly the same as those presented there. Moreover, if we had used the coefficient of correlation between a firm's residual from the regression of  $d_{ij}$  on  $P_{ij}$  and  $\ln S_{ij}$  (or  $S_{ij}$  alone if data on  $P_{ij}$  are lacking) for one innovation and that for another innovation, it would have made little difference either.

### 8. Summary and Conclusions

The results indicate that the length of time a firm waits before using a new technique tends to be inversely related to its size and the profitability of its investment in the innovation. For the innovations for which we could obtain data, the elasticity of the delay with respect to size of firm is about  $-.40$  and the elasticity of the delay with respect to the profitability of the investment ranges from  $-.03$  to  $-1.53$ .

If the differences in size or the profitability of the investment in the innovation are substantial, these relationships seem to be quite useful for purposes of prediction. For example, if one firm is four times as large as another (the profitability of the investment in the innovation being the same for both), the chance that it will introduce an innovation more rapidly than its smaller competitor seems to be about  $.80$ . Similarly, if the innovation is considerably more profitable for one firm than for another (of equal size), the probability is generally quite high that the former firm will be quicker to introduce it.

Holding firm size and the profitability of the investment in the innovation constant, there is no significant tendency for the length of time a firm waits to be inversely related to its profitability, its growth rate, and its liquidity, or directly related to the age of its president and its profit trend. Although these factors might seem to be important, their effects are often in the "wrong" direction and they are always statistically non-significant.

The results also indicate that technical leadership of this kind has not been very highly concentrated in most of the industries for which we have data. Even if one firm was considerably quicker than another to begin using one innovation, the chance that it will also be quicker to introduce another innovation occurring only five years later is not much better than 50-50. Apparently, there is no particular group of firms that consistently exercises leadership of this kind and no particular group that consistently brings up the rear.

These findings have at least four implications. First, they support the general proposition that the speed at which a firm responds to an investment opportunity is directly related to the profitability of the opportunity. This proposition, which is akin to the psychological laws relating the speed of response to the extent of the stimulus, has played an important role in studies of the imitation process and will undoubtedly prove useful in other areas too.

Second, the results seem to contradict the view held by some economists

that increases in size result in such sluggish performance that large firms tend to follow the lead of small ones. On the contrary, it appears that,  $P_{ij}$  held constant, one can predict with considerable confidence that a large firm will be quicker than a small one to begin using a new technique. Of course, this tells us nothing about the effects of market structure on the rate of imitation, but it does indicate that, holding market structure and  $P_{ij}$  constant, the larger firms can be expected to be the early users of new techniques.

Third, the results seem to indicate that a firm's financial health as measured by its profitability, liquidity, and growth rate, bears no close relationship to how long it waits before introducing a new technique. Whereas some relatively prosperous members of an industry tend to be quick to introduce an innovation, others tend to be slow. Holding  $S_{ij}$  and  $P_{ij}$  constant, the relationship seems to be quite weak, if existent at all. Perhaps these variables are less important than other more elusive and essentially non-economic variables. The personality attributes, interests, training, and other characteristics of top and middle management may play a very important role in determining how quickly a firm introduces an innovation. The presence or absence of a few men in the right places who believe strongly in the value of the new technique may make a crucial difference.

Fourth, the results show quite clearly the dangers involved in the common assumption that certain firms are repeatedly the leaders, or followers, in introducing new techniques. It would be very misleading to take a few innovations and assume that the firms that are quick to use them are generally the leaders in this sense. Judging by our findings, there is a very good chance that these firms will be relatively slow to introduce the next innovation that comes along.

In conclusion, the limitations of the study should be noted. The data we could obtain are limited in quality and scope; and because they are almost impossible to measure, we had to omit many important factors -- the

amount of research a firm conducted in the relevant area, the preferences of its management with respect to risk, the age of its old equipment, and the extent to which manufacturers of the new equipment could exert pressure on it. The results are only a first step toward understanding the factors determining whether one firm will be quicker than another to use an innovation, but despite their obvious limitations, they should be useful to economists concerned with the process of technical change.

REFERENCES

- [1] American Mining Congress, Coal Mine Modernization Yearbook, (annual).
- [2] Association of Iron and Steel Engineers, The Modern Strip Mill, (Pittsburgh, 1941).
- [3] Bohlen, J., and G. Beal, How Farm People Accept New Ideas, Special Report No. 15, Agricultural Extension Service, Iowa State College, 1955.
- [4] Camp, J., and C. Francis, The Making, Shaping, and Treating of Steel, (U.S. Steel Co., 1940).
- [5] Carter, C., and B. Williams, Industry and Technical Progress, (Oxford University, 1957).
- [6] Coleman, J., E. Katz, and H. Menzel, "The Diffusion of an Innovation Among Physicians," Sociometry, (December 1957).
- [7] Griliches, Z., "Hybrid Corn: An Exploration in the Economics of Technological Change," Econometrica, (October 1957).
- [8] Healy, K., "Regularization of Capital Investment in Railroads," Regularization of Business Investment, (National Bureau of Economic Research, 1954).
- [9] Hildebrand, P., and E. Partenheimer, "Socioeconomic Characteristics of Innovators," Journal of Farm Economics, (May 1958).
- [10] Kendall, M. G., The Advanced Theory of Statistics, (Hafner, 1951).
- [11] Jewkes, J., I. Sawers, and K. Stillerman, The Sources of Invention, (St. Martin's Press, 1958).
- [12] Mack, R., The Flow of Business Funds and Consumer Purchasing Power, (Columbia University, 1941).
- [13] Mansfield, E., "Technical Change and the Rate of Imitation," Econometrica, (October 1961).
- [14] \_\_\_\_\_, "Size of Firm, Market Structure, and Innovation," (abstract) Econometrica, (July 1961).
- [15] \_\_\_\_\_, "Intrafirm Rates of Diffusion of an Innovation," Cowles Foundation Discussion Paper No. 132.

- [16] \_\_\_\_\_, and H. Wein, "A Model for the Location of a Railroad Classification Yard," Management Science, (April 1958).
- [17] March, J. and H. Simon, Organizations, (Wiley, 1958).
- [18] Scitovsky, T., "Economics of Scale and European Integration," American Economic Review, (March 1956).
- [19] Stigler, G., Testimony before Subcommittee on Study of Monopoly Power, Judiciary Committee, House of Representatives, 1950.
- [20] Stocking, G., Testimony before Subcommittee on Study of Monopoly Power, Judiciary Committee, House of Representatives, 1950.
- [21] Sutherland, A., "The Diffusion of an Innovation in Cotton Spinning," The Journal of Industrial Economics, (March 1959).
- [22] Yance, J., "Technological Change as a Learning Process: The Dieselization of the Railroads," (Unpublished, 1957).

FOOTNOTES

\* The work on which this report is based was supported financially by the Graduate School of Industrial Administration at Carnegie Institute of Technology, the Office of Special Studies of the National Science Foundation, The Ford Foundation, and the Cowles Foundation for Research in Economics at Yale University. It is part of a broader study of research, technical change, and economic growth that I am conducting. My thanks go to the many people in industry who provided information and to K. Healy, A. Meltzer, J. Muth, and R. Nelson for their helpful comments.

1/ In recent years, studies of the imitation process have been carried out by Bohlen and Beal [3], Coleman, Katz and Menzel [6], Griliches [7], Hildebrand and Partenheimer [9], Mansfield [13, 15], Sutherland [21], and Yance [22]. But only a few of these studies have been concerned with the factors influencing a particular firm's speed of response, and those that have been concerned with these factors have pertained almost always to agriculture. This seems to be the first study pertaining to the industrial sector.

2/ Not all economists seem to agree with this proposition. For example, Stocking [20], p. 966, in discussing this question, has asserted that pioneering is unlikely to occur where "bureaucracy, red tape, and a quest for security... afflict private industry...[and] the likelihood of their doing so varies directly with the size of a firm." Although it is undoubtedly true that increases in size are sometimes accompanied by unwieldiness and conservatism, it seems unlikely to me that they generally can offset the factors noted above.

On the other hand, Carter and Williams [5, p. 186] conclude that, while technical progressiveness is possible for firms of all sizes, small firms often operate with certain handicaps that make technical progress particularly difficult for them to achieve. Scitovsky [18, p. 78], although he is concerned with a somewhat different problem seems to be impressed with the advantages of size in this connection. Bohlen and Beal [3] present evidence to the effect that the large firms tend to be quicker to introduce new agricultural techniques.

3/ To illustrate the second point in the text, consider an innovation that can be used in only a certain type of coal mine when it is first commercialized at time  $t_1$ , but that is made applicable to all mines at time  $t_2$ . Assume (for simplicity) that each mine has the same chance --  $P$  -- of being able to accommodate the innovation at first and that this chance does not depend on whether other mines under the same ownership can accommodate it. If each firm begins using it as soon as it can, one can show that

$$E(d_j) = (1 - P)^{S_j/A} (t_2 - t_1),$$

where  $E(d_j)$  is the expected value of the number of years the  $j^{\text{th}}$  firm will



Footnote 3 (continued)

wait (dating from  $t_1$ ) before introducing it,  $S_j$  is its output rate, and  $A$  is the output rate per mine. As expected, there is an inverse relationship between  $E(d_j)$  and  $S_j$ .

To illustrate the third point in the text, suppose that an innovation occurs at time  $t$  and that the number of years -- measured from time  $t$  -- before a unit of old equipment can profitably be replaced by the innovation is a random variable,  $i$ , with probability density

$$P(i) = \phi^{-1} \quad (0 \leq i \leq \phi)$$

If we assume that the number of years before one unit can be replaced is statistically independent of that for another unit and if the number of units owned by a firm is proportional to its output rate, it follows that

$$E(d_j) = \phi (S_j/C + 1)^{-1},$$

where  $C$  is the output rate per unit of the replaced equipment. As expected, there is an inverse relationship between  $E(d_j)$  and  $S_j$ .

<sup>4/</sup> This model incorporates both the second and third reasons given in the preceding section for expecting that large firms will lead small ones. The results in note 3 are special cases. Note that the first reason is omitted entirely here.

The assumption that  $F(x)$  is the same for each unit and that the  $x$ 's are independent is not very realistic, but small departures from it should make little difference. The results are used only to get a rough idea of the shape of the relationship between a firm's size and its speed of response.

<sup>5/</sup> Given  $F(x)$ , the probability density function for the smallest  $x$  can easily be shown to equal  $\alpha[1 - F(x)]^{\alpha-1}F'(x)$ . Thus equation (1) follows.

Integrating equation (1) by parts, we find that  $E(\alpha) = -x[1 - F(x)]^\alpha \Big|_0^M + \int_0^M [1 - F(x)]^\alpha dx$ . Since the first term equals zero, equation (2) follows.

Equations (3) and (4) follow simply, and since  $0 \leq F(x) \leq 1$ , the indicated inequalities hold.

6/ There is considerable agreement that the profitability of a new technique determines how quickly a firm begins using it. See Mansfield [13], Griliches [7], Mack [12], and Sutherland [21].

7/ Other functional forms were used to see whether the results were sensitive to the particular form used. First,  $d_{ij}$  was assumed to be a linear function of  $P_{ij}$  and  $\ln S_{ij}$ . Second,  $\ln d_{ij}$  was assumed to be a linear function of  $S_{ij}$  and  $P_{ij}$ . In both cases, all the regression coefficients were allowed to vary from one innovation to another. The results were qualitatively similar to those obtained below.

Note that  $a_3$  may differ somewhat from innovation to innovation, depending on the size of the investment required to introduce the innovation and the average profitability of the investment in the innovation. We assume that the differences in  $a_3$  among these innovations are relatively small.

8/ For descriptions of these innovations, see Association of Iron and Steel Engineers [2] for the strip mill, Camp and Francis [4] for continuous annealing and the by-product coke oven, annual issues of Coal Age on mechanization and American Mining Congress [1] for the innovations in coal, Fortune (January 1936) for the tin container, American Brewer (September 1954) for pallet loaders and other issues for high-speed bottle fillers, Jewkes, et. al., [11] for the diesel locomotive, Mansfield and Wein [16] for car retarders, and Healy [8] for the other railroad innovations.

9/ For the continuous wide strip mill, all firms having more than 140,000 tons of sheet capacity in 1926 were included; for the by-product coke oven, all firms having more than 200,000 tons of pig iron capacity in 1900 were included; and for continuous annealing, the nine major producers of tin plate in 1935 were included. For centralized traffic control and car retarders, all Class I railroads with over 5 billion freight ton-miles in 1925 were included. For the mikado and the trailing-truck locomotive, the roads included in Healy's sample [8] are included. All Class I railroads in 1925 are included for the diesel locomotive. Firms producing over 4 million tons of coal in 1956 were included for the coal innovations, and firms with more than \$1 million in assets in 1934 were included for the brewing innovations.

These lower limits on size were imposed because of difficulties in obtaining information concerning smaller firms and because in some cases they could not use the innovation in any event. As it is, data could not be obtained for all these firms because some went out of business or refused to cooperate. But in most cases the results are complete -- or very nearly so. For a more detailed discussion, see [13].

The date when each firm first introduced the innovation was obtained from trade journals, industry directories, and correspondence with the firms.

There were a handful of firms for which no data could be obtained and they had to be excluded. The specific sources of these data are listed in the Appendix of Mansfield [13].

Note that these are the dates when firms first introduced the innovation -- regardless of the scale on which they did so. The possible objections to this are largely removed by the fact that most of these innovations had to be introduced on a large scale. And in the case of the diesel locomotive, one of the few cases where the innovation did not have to be introduced on such a large scale, we made sure that the dates of first purchase almost always represented dates when a substantial number of diesel locomotives were bought, not dates when a trivial number were acquired.

Moreover, the only alternative would be to use the date when a firm first used the innovation to produce some specified percentage of its output, and in almost every case it would have been extremely difficult, if not impossible, to obtain such data. For a study of one case where data of (roughly) this type were available, see Mansfield [15].

10/ For the railroads, the data on freight ton-miles come from the Interstate Commerce Commission's Statistics of Railways and pertain to 1925. For the coal firms, the production data come from Moody's and relate to 1939 for the trackless mobile loader and the shuttle car. For the continuous mining machine, they come from Moody's and the Keystone Guide and relate to 1947-48. For the by-product coke oven, the pig iron capacities come from the 1901 Directory of the American Iron and Steel Institute; for the continuous wide strip mill, the ingot capacities come from the 1926 Directory of the American Iron and Steel Institute; for continuous annealing, the size data are sales volumes taken from Moody's for 1935. For high-speed bottle fillers and the pallet-loading machine, production data came from Modern Brewery Age and they pertain to 1955; for the tin container, the data are production estimates for 1940 from the Brewers Journal (July 15, 1943).

11/ According to interviews with coal executives, a firm with relatively little coal from 4 to 9 feet high would almost surely not find continuous mining machines as profitable as a firm with most of its coal in that range. The greater profitability of the innovation in this range was also pointed out by Bituminous Coal Research, Inc. in a private report. For each firm, the per cent of its capacity in this range was computed from the 1949 Keystone Coal Buyer's Guide and this rather crude measure was used as a surrogate for the profitability of the investment.

As noted previously, the introduction of diesel locomotives seemed more profitable for firms that hauled little coal. This factor was often cited in the interviews, and its importance has been stressed by Yance [21]. Moreover, according to railroad officials, centralized traffic control was probably less profitable for roads with little double track. The per cent of trackage that was double and the per cent of revenues derived from coal come from Moody's. They pertain to 1926 and 1935.

We also noted previously that, according to the interviews, there were considerable economies of scale for the continuous rolling mill and continuous annealing. For given over-all size, it would therefore seem that those firms that specialized most heavily in sheets or tin plate would have found them most profitable. Moreover, these firms had the most to lose by delay. A firm's sheet capacity divided by its ingot capacity was computed from the 1926 Directory of the American Iron and Steel Institute; a firm's tin plate capacity as a per cent of its ingot capacity was computed from the 1940 Directory. Of course, these measures are very crude.

12/ Of course, the assumption that  $P_{ij} = R_i H_{ij}$  is bold, but it may not be too bad a first approximation.

13/ The number of firms for each innovation is 71 (diesel locomotive), 12 (continuous mining machine), 12 (continuous wide strip mill), 9 (continuous annealing), 23 (centralized traffic control), 11 (shuttle car), 11 (trackless mobile loader), 19 (tin container), 18 (pallet loading machine), 15 (high speed bottle filler), 12 (by-product coke oven), 28 (trailing-truck locomotive), 22 (car retarders), and 32 (mikado locomotive).

14/ These results indicate that firms for which the potential returns were highest -- because of their physical set-ups, market situations, etc. -- tended to be early users of the innovation. Note that the data are such that the line of causation can not be turned about. These results can not possibly be a mere reflection of the fact that early users, by virtue of their quickness, often enjoy a somewhat higher return. E.g., the per cent of a firm's revenues derived from coal or the per cent of its output derived from high seams could hardly be affected by its speed of response to these innovations.

Note that some firms had not yet begun using high-speed bottle fillers. We included them by assuming that they would introduce them in 1963. Of course, this makes the results for this innovation rather arbitrary, but it would also have been misleading to exclude them altogether.

15/ For a description of these interviews, see Mansfield [13]. In passing, the following points might be noted, since they help to integrate our present data and findings with those presented in [13]. First, it should be noted that our finding in this paper that the larger firms tend to lead does not contradict our finding there that the rate of imitation tends to be lower in more highly concentrated industries. The results presented here for a particular innovation are based implicitly on a certain industry structure, and how long a firm of given size waits may depend on this structure (and the extent of concentration). Second, two innovations are included here but not in [13] because of lack of necessary auxiliary data. Third, the firms included here sometimes differ slightly from those included there. For the sake of greater homogeneity we excluded steel firms in dealing with the coal innovations and excluded the switching roads in the case of the car retarders. We also included all Class I roads for the diesel locomotive. Where size data could not be obtained firms had to be omitted. For further integration of our results with those obtained in [13], see note 19.

<sup>16/</sup> Note two things here. (1) In the railroad, brewing, and coal industries, there was almost complete agreement with respect to innovations requiring a fairly large investment. But for techniques that could be installed very cheaply there was less agreement that the larger firms lead. On the basis of the reasoning in Section 2, one might anticipate that the larger firms would lead less consistently if very small amounts of capital were required. (2) The impression that the largest firms do not lead in the steel industry can be found in congressional hearings and popular business literature as well as in these interviews. But in almost all of this literature, the performance of U.S. Steel is contrasted with some of its smaller competitors. Although it may tend to lag behind some of them, there may nonetheless be an inverse relationship between size and delay in the whole industry. Moreover, differences among firms in the profitability of the innovation are not taken into account. See Fortune (March 1936), Stocking [20], and Stigler [19].

<sup>17/</sup> Given that the hypothesis holds (i.e., given that equation (5) holds and that  $a_3$  is negative), it follows that the probability that a firm  $X$  times as large as another will be quicker to introduce the innovation is

$$\begin{aligned}
 \Pr \left\{ \ln d_k < \ln d_l \right\} &= \Pr \left\{ a_{i1} + a_3 \ln S_{ik} + a_{i2} \ln P_{ik} + \epsilon_{ik} < a_{i1} + a_3 \ln S_{il} \right. \\
 &\quad \left. + a_{i2} \ln P_{il} + \epsilon_{il} \right\} \\
 &= \Pr \left\{ a_3 \ln S_{ik} + \epsilon_{ik} < a_3 \ln S_{il} + \epsilon_{il} \right\} \\
 &= \Pr \left\{ a_3 \left[ \ln S_{il} + \ln X \right] + \epsilon_{ik} < a_3 \ln S_{il} + \epsilon_{il} \right\} \\
 &= \Pr \left\{ a_3 \ln X + \epsilon_{ik} < \epsilon_{il} \right\} \\
 &= \Pr \left\{ \epsilon_{il} - \epsilon_{ik} > a_3 \ln X \right\} \\
 &= 1 - U \left[ a_3 \ln X / \sigma_\epsilon \sqrt{2} \right] \\
 &= U \left[ -a_3 \ln X / \sigma_\epsilon \sqrt{2} \right]
 \end{aligned}$$

18/ One can go through the same sort of procedure as that carried out (in connection with  $S_{ij}$ ) in note 17. But the added difficulty here is that  $a_{i2}$  (unlike  $a_3$ )<sup>ij</sup> varies from innovation to innovation.

19/ It can be shown that the rate of imitation in the case of the  $i^{\text{th}}$  innovation is a decreasing function of  $a_{i2}^2$ ,  $\sigma_\epsilon^2$ , the variance of  $\ln H_{ij}$ , and the variance of  $\ln S_{ij}$ . Thus the fact that  $a_{i2}$  seems to be an increasing function of the average profitability of the investment in the innovation and a decreasing function of the size of the required investment would be expected on the basis of our findings in [13].

20/ However, because the uncontrolled effects of  $P_{ij}$  inflate the residuals, the correlation coefficient is only .35 in the case where data on only  $S_{ij}$  are available. Had it been possible to include smaller firms, the relationship would probably have been stronger. In only two cases was it possible to extend the analysis on an exploratory basis. For the continuous mining machine, data were collected for all firms producing over 100,000 tons in 1948 from the listings of equipment in the Keystone Coal Buyers Guide. As size decreased, a smaller percentage had installed continuous miners as yet, and those that did had installed them later. For centralized traffic control, data for a somewhat larger group of firms were obtained from Healy [8], and the results were much the same. Of course, the data used here are less reliable than those on which Tables 1-3 are based.

21/ See note 7. The one exception was the trailing truck locomotive, where the relationship between  $S_{ij}$  and  $d_{ij}$  was direct, but not statistically significant.

22/ See Mansfield [13], note 26 for further discussion of the effects of this factor.

23/ Ruth Mack [12], p. 289, quotes one machinery manufacturer as saying that the early purchasers tend to be "either the 'wide-awake progressive companies' which were generally...in a strong financial position or the 'do or die' group which decided to play a turn of the wheel and sink or swim thereby." According to him, the first group was the more important.

<sup>24/</sup> Specifically,  $g_{ij}$  is 100 times the ratio of the sales (or freight ton-miles in the case of railroads) in the terminal year to that in the initial year:

<u>Innovation</u>	<u>Terminal Year</u>	<u>Initial Year</u>	<u>Period for <math>\Pi_{ij}</math></u>
Continuous mining machine	1958	1948	1946-48
Shuttle car and trackless mobile loader	1948	1938	1938-40
Continuous annealing	1956	1936	1939-41
Continuous strip mill	1936	1926	1926-28
Bottle filler and pallet loader	1958	1950	1950-52
Railroad innovations	1949	1925	1925-27

The period to which  $\Pi_{ij}$  pertains, is provided in the final column. The data came from Moody's and the Statistics of Railways. Of course, only firms for which such data could be obtained were included in the regressions. (Three innovations were excluded altogether because of lack of data.)

Of course, if equation (6) -- or equations (7) or (8) -- is the true model there is a bias in the estimates because of specification error. But it does not appear that this bias is very important. The estimates of  $a_{12}$  and  $a_3$  are not very different from the corresponding estimates of  $b_{12}$  and  $b_3$ .

<sup>25/</sup> The correlation coefficients were .64 (for innovations where data only were available) and .50 (for innovations where such data were not available). The number of firms included for each innovation were 65 (diesel locomotive), 8 (continuous mining machine) 10 (continuous wide strip mill), 9 (continuous annealing), 23 (centralized traffic control), 9 (shuttle car), 9 (trackless mobile loader), 7 (pallet loading machine), 6 (high speed bottle filler), 21 (trailing truck locomotive), and 22 (car retarders). Note that the data are rather crude. The growth data pertain only to very long periods and the rate of growth within these periods was probably far from smooth. The data on  $\Pi_{ij}$  pertain only to a three-year period.

26/ Although the hypothesis that  $A_{ij}$  is an important determinant of  $d_{ij}$  seems dubious on a number of counts, the results of the agricultural studies indicated that it was worthy of investigation. Data were obtained from Moody's, Standard and Poor's Register of Executives, Who's Who, etc., regarding the age of the president of each firm when the innovation first was used. Of course, there is a problem of timing here.

The correlation coefficients were .70 (for innovations where data on  $P_{ij}$  were available) and .51 (for the others). The number of firms included for each innovation was 8 (continuous mining machine), 10 (continuous wide strip mill), 9 (continuous annealing), 23 (centralized traffic control), 9 (shuttle car), 9 (trackless mobile loader), 7 (pallet loading machine), 21 (trailing truck locomotive), and 22 (car retarders).

27/ This part of the paper benefited from discussions with G. von der Linde. The basic data were obtained by K. E. Knight in a term paper. Profits plus bond interest divided by total sales was used as the profit rate for the railroads and profits less preferred dividends divided by net worth were used for the coal and steel firms. Somewhat different measures might have been used instead, but the results would almost certainly have been about the same. Again, the period of time to which the exogenous variables pertain may not be exactly what one would ideally want here.

The correlation coefficient was .64, the number of firms included for each innovation was 65 (diesel locomotive), 9 (continuous mining machine), 9 (continuous annealing), and 23 (centralized traffic control).

28/ Note that, in Sections 6-7, the results regarding the effects of  $g_{ij}$ ,  $\Pi_{ij}$ ,  $A_{ij}$ ,  $L_{ij}$ , and  $t_{ij}$  turn out to be essentially the same if we do not constrain their "elasticities" to be the same from one innovation to another.

29/ Firms with aggressive managements often lose their taste for pioneering as those managements grow older or as others take their place; and laggard firms sometimes change their ways because of an injection of new blood and capital. With the passage of time, it becomes increasingly likely that those that were particularly receptive to change in a past era have given up this role to others.

30/ Note that, although the coefficient of correlation between how rapidly a firm introduced one innovation and how rapidly it introduced another is a reasonable measure of the extent to which leadership is concentrated, it has certain obvious disadvantages and it is not the only measure that might be used. E.g., the coefficient of rank correlation is a possible alternative measure and it, too, is used below.

Note too that it is impossible for the linear function in equation (9) to be applicable throughout the entire range, but it may be a useful local approximation.



31/ The results of the analysis of covariance are as follows:

<u>Source of Variation</u>	<u>Sum of Squares</u>	<u>Degrees of Freedom</u>
Overall slope (w)	.0917	1
Slope of means versus w	.2122	1
Means about regression of means	.0273	2
Industry slopes versus w	.1895	3
Residual	.3577	11

For a description and interpretation of the analysis of covariance, see Kendall [10].

32/ Of course, one important reason why there is a tendency for the same firms to be the leaders is that the large firms tend to be the leaders and the same firms tend to be large during periods of relevant length. However, this is not the whole story. If a firm's residual from the regression of  $d_{ij}$  on  $P_{ij}$  (when data are available) and  $\ln S_{ij}$  is used, rather than  $d_{ij}$ , the results are much the same. Thus, if one corrects roughly for a firm's size, there is still some tendency for the same firms to be the leaders.

33/ Let  $d_{1j}$  and  $d_{1k}$  be the delays for the  $j^{\text{th}}$  and  $k^{\text{th}}$  firms in introducing the first innovation. Let  $d_{2j}$  and  $d_{2k}$  be their delays in introducing the second innovation. We suppose that in general for the  $i^{\text{th}}$  firm,

$$d_{2i} = Q_0 + Q_1 d_{1i} + V_i,$$

where  $Q_0$  and  $Q_1$  are parameters and  $V_i$  is a normally distributed random variable with zero expected value. What is the probability that  $d_{2j} < d_{2k}$ , given that  $d_{1j} < d_{1k}$ ?

It equals

$$\begin{aligned} & \Pr \left\{ Q_0 + Q_1 d_{1j} + v_j < Q_0 + Q_1 d_{1k} + v_k \right\} \\ &= \Pr \left\{ Q_1 (d_{1j} - d_{1k}) < v_k - v_j \right\} \\ &= 1 - U \left[ Q_1 (d_{1j} - d_{1k}) / \sigma_v \sqrt{2} \right] \end{aligned}$$

If  $d_{1i}$  was normally distributed and  $d_{1k}$  was at the 75<sup>th</sup> percentile and  $d_{1j}$  was at the 25th percentile,  $d_{1j} - d_{1k} = -1.34\sigma_d$ , where  $\sigma_d$  is the standard deviation of the  $d_{1i}$ . Thus, the probability equals

$$1 - U \left[ -1.34 Q_1 \sigma_d / \sigma_v \sqrt{2} \right]$$

But it can easily be shown that  $Q_1 \sigma_d / \sigma_v = \sqrt{r^2 / (1-r^2)}$ . Thus, we have

$$1 - U \left[ -1.34 \sqrt{r^2 / (2(1-r^2))} \right],$$

where  $r$  is the coefficient of correlation between  $d_{1i}$  and  $d_{2i}$ .

Inserting .25 for  $r$ , we get the result (.59) in the text.

Note too that, because the linear approximation in equation (9) is unlikely to hold very well for extreme values of  $t_{qr}$ , the estimates of  $v$  are probably only rough estimates of the values of  $\rho_{qr}$  when  $t_{qr}$  is extremely small. But for values of  $t_{qr}$  of one or more, the results may be quite good.

Finally, although a firm's rate of response to a recent innovation is not very useful in most of these industries as a predictor of its rate of response to a current one, it is as good a predictor as a firm's size when  $P_{ij}$  is not held constant. (Of course, this is not surprising since, as pointed out in note 32, one important reason for  $\rho_{qr}$  being greater than zero is the size effect.) But when  $P_{ij}$  is held constant, a firm's size seems to be an appreciably better predictor than a firm's rate of response to a previous innovation.

34/ If a few firms continually spend much more on research of practically all sorts (relative to their size) than the others, they may tend to be the leaders again and again. Note too that the extent to which the same firms tend to be leaders may be affected by the extent to which the innovations differ with regard to such characteristics as capital requirements, the sorts of firms for which they are most profitable, etc. The less the innovations differ in these respects, the more likely that the same firms will tend to be the leaders.