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INTRAFIRM RATES OF DIFFUSION OF AN INNOVATION*

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1. Introduction

In recent years, economists have shown a lively, and growing, interest in the factors determining how rapidly a new technique is substituted for older methods. This rate of substitution, or rate of diffusion, merits such attention because it determines how rapidly productivity rises in response to the new technique. Since the rate of increase of productivity is directly related to the rate of diffusion, the full social benefits from the innovation will not be realized if the diffusion process goes on too slowly.1/

This paper studies for the first time the intrafirm rate of diffusion -- the rate at which a particular firm, once it has begun to use a new technique, proceeds to substitute it for older methods.2/ Once they become familiar with an innovation, some firms abandon the older technology and replace it very quickly with the new. Others are much slower to make the transition. Given that a firm has begun to use a new type of equipment, what determines how rapidly it goes on to substitute it for an older type?

This question is important because the intrafirm rates of diffusion determine in part the rate of diffusion in the entire industry.3/ To help answer it, we single out one of the most significant innovations that occurred in the interwar period -- the diesel locomotive. We construct and test an econometric model to help explain differences among railroads in the rate at which, once they had begun to dieselize, they substituted diesel motive power for steam. Although this model is rough and over-simplified, it seems to stand up quite well; and with appropriate modification, it is likely to prove useful for other innovations too.

The plan of the paper is as follows. Section 2 provides a brief historical sketch of the nation-wide displacement of the steam locomotive by the diesel. Section 3 describes the differences among railroads in how rapidly, once they had begun to dieselize, they substituted diesel power for steam. Sections 4 - 5 present and test a simple model to help explain these differences, and Section 6 discusses the effects of some additional factors, and Section 7 analyzes utilization rather than ownership data. Section 8 contains a summary and conclusions.

2. Nation-wide Substitution of Diesel Power for Steam

We begin by considering the overall process whereby the diesel locomotive displaced the steam locomotive. For present purposes, the story begins in 1924, when the first diesel locomotive was used in this country -- and eleven years after the diesel-electric system was first used in Europe.[4/] The early diesel locomotives were heavy, slow, and without much power. By 1930, eleven American roads used them at some point on their properties, but they were usually installed where there was a smoke nuisance or a fire hazard.[5/]

During the Thirties, diesel locomotives became more important in the United States. In 1933, General Motors came out with an improved locomotive that was smaller, faster, and more powerful than previous types and in 1934, there began the era of the diesel "streamliners."[6] By 1935, 50 percent of of the major American railroads had begun to use diesel locomotives (see Table 1), these leaders generally being large firms and firms where the investment in such locomotives was particularly profitable. In particular, they tended to haul little coal. The "coal roads" were reluctant to install diesel locomotives because it might alienate their important customers and because coal was relatively cheap for them.[7]

By 1940, according to a small-scale survey conducted in connection with this paper,[8] most major American railroads seemed to regard the diesel switcher as being completely out of the experimental stages, although there was still considerable uncertainty regarding its maintenance costs and other factors governing its profitability. When we entered World War II, the diesel locomotive had gained considerable acceptance for switching and limited acceptance for other purposes. By that time it accounted for about three-fourths of new orders (according to [7], p. 14).[9]

Defense needs and priorities governed the production and allocation of diesel locomotives during the war. The allocation of diesel power among the nation's railroads was controlled by the Office of Defense Transportation, and the locomotive builders were allocated material by the War Production Board. Because of the wartime increases in traffic and the change in traffic flows, there was a considerable need for new motive power to replace many of the old steam locomotives. At first, materials (particularly for the diesel power plant) were very tight. But as time went on and the need became more pressing, controls were relaxed and the production of diesel locomotives was stepped up considerably.[10]

Table 1 - Number of Diesel and Steam Locomotives and Number of Major Railroads Using Diesel Locomotives, United States, 1925-59.

	Diesel Locomotives		Steam Locomotives		Major Users a/	
Year (Dec. 31)	Number	Percent of Total	Number	Percent of Total	Number	Percent of Total
1925	1	b/	67,713	99.4	1	4.2
1927	14	b/	64,843	99.2	8	33.3
1929	25	b/	60,572	98.9	9	37.5
1931	80	.1	57,820	98.6	10	41.7
1933	85	.2	53,302	98.3	10	41.7
1935	130	.3	48,477	97.9	12	50.0
1937	293	.6	46,342	97.4	14	58.3
1939	639	1.4	43,604	96.5	19	79.2
1941	1,517	3.4	41,911	94.4	21	87.5
1943	2,476	5.5	41,983	92.5	23	95.8
1945	4,301	9.3	41,018	88.7	23	95.8
1947	6,495	14.6	36,942	83.3	23	95.8
1949	12,025	27.8	30,344	70.1	23	95.8
1951	19,014	44.8	22,590	53.2	23	95.8
1953	24,209	65.0	12,274	32.9	23	95.8
1955	26,563	79.2	6,266	18.7	24	100.0
1957	29,137	90.0	2,608	8.1	24	100.0
1959	30,097	95.4	871	2.8	24	100.0

Source: *Statistics of Railways* [10], 1925-60.

a/ Only railroads with more than 5 billion freight ton-miles in 1925 are included. This group differs slightly from that used in Mansfield [12]. See the Appendix of the latter paper for the differences. A railroad is counted as a "user" if it owned one or more diesel locomotives.

b/ Less than one-tenth of one percent.

During the war, about 2,800 diesel locomotives were acquired by American railroads, and by the end of 1945, they constituted almost ten percent of the total locomotive stock.

When the war ended the acceptance of the diesel locomotive was widespread, but few firms expected it to displace the steam locomotive for all types of work. For example, only four of the seventeen firms for which we have data planned at that time to dieselize completely.[11/] However, as time went on, several developments helped to make the advantages of complete dieselization more obvious. First, further refinements were made in diesel design, and the price per horsepower of the diesel locomotive continued to decline relative to steam.[12/] Second, it became obvious that large savings could be effected by completely eliminating the facilities needed to service and repair steam locomotives. Third, the remaining uncertainties regarding the diesel locomotive's performance and maintenance were largely dispelled, and the problems in training crews and ancillary personnel were met -- with the assistance of the locomotive manufacturers.[13/]

Between 1946 and 1955, most of the firms for which we have data decided to dieselize completely. Because they were closer to complete dieselization when the decision was made, they generally planned to accomplish it in only three or four years -- rather than in the ten-year period planned by those that made the same decision in 1945. As a rule, these plans were carried out on time, and by 1959, the diesel locomotive had almost completely displaced the steam locomotive.[14/]

3. Intrafirm Rates of Diffusion

Although the previous section provides the necessary background, it tells us very little about the rate at which particular railroads, once they had begun to dieselize, substituted diesel motive power for steam. Table 2 provides some information on this score. It shows how long it took 30 randomly chosen firms to increase their stock of diesel locomotives from 10 percent to 90 percent of their total locomotive stock. Of course, this is only a crude measure of the intrafirm rate of diffusion, because it arbitrarily regards the date when 10 percent of a firm's locomotives were diesels as the date when it "began" to dieselize. Moreover, it arbitrarily regards the date when 90 percent of a firm's locomotives were diesels as the date when it was "entirely" dieselized.[15]

Despite its limitations this measure is a reasonable first approximation that should do for present purposes, although it will be replaced by a better measure in the following section. In interpreting this measure, note that it does not indicate how rapidly a firm accepted the diesel locomotive, as measured by the rate at which diesels came to dominate the firm's locomotive purchases. Although it is influenced by this factor, it also reflects the rate at which steam locomotives were scrapped and the rate at which locomotives of all kinds were purchased. Since we are interested in the effect of the rate of diffusion on productivity, the latter factors must also be included.[16]

Note too that this measure provides no information regarding the date when various railroads "began" to dieselize. Since previous papers [12, 13] investigated the factors determining how rapidly a firm begins to use an innovation (the diesel locomotive and others), we simply take these dates as given and focus our attention

Table 2 - Time interval between date when diesel locomotives were 10 percent of all locomotives and date when they were 90 percent of all locomotives, 30 randomly chosen Class I railroads.[a]

Time Interval	Number of Firms	Percentage of Firms
14 or more years	3	10
11-13 years	7	23
8-10 years	11	37
5-7 years	3	10
3-4 years	6	20
TOTAL	30	100

Source: Statistics of Railways [10], 1925-61.

[a] The railroads included here are listed in Table 3. We assumed that the Duluth, Missabe, and Iron Range Railroad would reach 90 percent of full dieselization in 1963.

on how rapidly a firm went on to substitute diesel power for steam. It might be noted, however, that these firms generally reached the point where diesels were 10 percent of their locomotive stock after World War II. Thus, when we deal with the results in Table 2, we are dealing almost exclusively with postwar developments.[17/]

Finally, returning to Table 2, the results indicate that there were substantial differences among firms in the rate of diffusion. Although nine years were required on the average to increase a firm's stock of diesels from 10 to 90 percent of the total, some firms took three years and others took sixteen. Once they had "begun" to dieselize, why did some firms make the transition so much more quickly than others? The material presented in the previous section is of limited use in answering this question, since it pertains mostly to industry-wide developments and to the period before the end of the war. The following sections present and test a simple model designed to help answer it.

4. A Simple Model

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 diesel. Assuming that the i^{th} firm's traffic volume and R_i remain approximately constant during the relevant period,[18/] the total number of locomotives owned by the i^{th} firm at time t is

(1) $$T_i(t) = N_i - (R_i - 1) D_i(t) .$$

And 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 Π_i be the rate of return that 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) , $U_i(t)$ be a measure of the apparent riskiness at time t of its making such an investment, S_i be a measure of its size, and C_i be a measure of its liquidity at the time when it "began" to dieselize. Letting

(2) $$W_i(t) = [D_i(t+1) - D_i(t)]/[N_i/R_i - D_i(t)] ,$$

we suppose that

(3) $$W_i(t) = f(\Pi_i , U_i(t), S_i, C_i, \ldots) .$$

The rationale for this hypothesis is as follows. Other things equal, how heavily a firm invested in diesel locomotives between time t and time $t+1$ certainly depended on how profitable and how risky such an investment seemed at time t . Thus, one would expect $W_i(t)$ -- the proportion of unfilled places that were filled with a diesel locomotive during this period -- to be directly related to Π_i and inversely related to $U_i(t)$.

Because more liquid firms were better able to finance the necessary investment and to take the risks, one might expect them, all other things equal, to have invested more heavily than other firms. Moreover, 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 investment (in absolute terms) required to convert, and perhaps because of the quicker process of decision-making in smaller units. Thus, $W_i(t)$ may be directly related to C_i and inversely related to S_i .[19]

Since $U_i(t)$ cannot be measured directly, we assume that

$$(4) \qquad U_i(t) = g(L_i, R_iD_i(t)/N_i, \dots) ,$$

where L_i is the time interval separating the year when the first firm (in this country) "began" using diesel locomotives from the year when the i^{th} firm "began" using them, and $R_iD_i(t)/N_i$ is the proportion of places in the i^{th} firm already filled at time t . Equation (4) assumes that, the longer a firm waited before "beginning" to use the diesel locomotive, the more knowledge it had derived from other firms' experiences with the diesel, and the less uncertainty it had regarding the diesel locomotive's profitability when it "began" to dieselize. It also assumes that, the nearer a firm was to full dieselization at time t (i.e., the 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.[20] Substituting equation (4) into equation (3), we have

$$(5) \qquad W_i(t) = h(\Pi_i, L_i, R_i D_i(t)/N_i, S_i, C_i, \ldots) ,$$

where, according to the model, $W_i(t)$ is directly related to each of the independent variables other than S_i .

Equation (5) is quite consistent with interview data and previous studies of the diffusion process. A dozen railroad officials when interviewed in connection with this study stressed the importance of each of these independent variables. The hypothesized effects of Π_i, L_i, and $R_i D_i(t)/N_i$ on $W_i(t)$ are consistent with results concerning the diffusion of other innovations. See Coleman, et al., [4], Griliches [8], Mansfield [12, 13], and Yance [20].[21]

Given equation (5), we assume that $W_i(t)$ can be approximated within the relevant range by a quadratic function of Π_i, L_i, ..., C_i , but that the coefficient of $[R_i D_i(t)/N_i]^2$ is zero. Then substituting the corresponding differential equation for the difference equation that results and recognizing that $\lim_{t \to -\infty} D_i(t) = 0$, we have

$$(6) \qquad D_i(t) = N_i \left\{ \left[R_i \quad 1 + e^{-(\alpha_i + V_i t)} \right] \right\} - 1 ,$$

where

$$(7) \qquad V_i = c_1 + c_2 \Pi_i + c_3 L_i + c_4 S_i + c_5 C_i + \epsilon_i ,$$

e_i is a random error term, and c_2, c_3, $- c_4$, and c_5 should be positive if the model holds. The argument leading up to equations (6) and (7) is exactly like that in Mansfield [12].[22]

Finally, if $P_i(t)$ is the proportion of the i^{th} firm's locomotives at time t that are diesels,

$$(8) \qquad P_i(t) = D_i(t)/T_i(t) ,$$

and substituting equations (1) and (6) into equation (8), we have

$$(9) \qquad P_i(t) = \left[1 + e^{-(\alpha_i' + V_i t)}\right]^{-1} .$$

Thus, if the model holds, the proportion of a firm's locomotives that were diesels should be a logistic function of time. And the parameter of this function measuring the intrafirm rate of diffusion, V_i , should be linearly related to Π_i, L_i, S_i, and C_i . In the following section, we see how well this model can explain the observed differences in intrafirm rates of diffusion.[23]

5. Tests of the Model

To test this model, we obtained data regarding $P_i(t)$ from the Statistics of Railways [10] for the 30 railroads in Table 2 for each year from 1925 to 1960.[24] Using ICC data and Moody's, we also obtained measures of L_i (the year when the i^{th} firm "began" to dieselize less 1941), S_i (the i^{th} firm's freight ton-miles in 1949), and C_i (the i^{th} firm's average ratio of current assets to current liabilities in the two years prior to and including when it "began" to use diesel locomotives). Rough estimates of Π_i were obtained mainly from correspondence with the firms.[25/] The estimates of L_i, S_i, and C_i appear in Table 3. The estimates of Π_i, which were obtained from the firms with the assurance that their replies would remain confidential, are omitted.

First, we use these data to see how well $P_i(t)$ conforms to a logistic function. If equation (9) holds,

$$\ln\,[P_i(t)/1 - P_i(t)] \;=\; \alpha_i' + V_i\, t\ . \tag{10}$$

Thus, one crude way to measure the goodness of fit of the logistic function is to see how well $\ln\,[P_i(t)/1 - P_i(t)]$ can be represented by a linear function of t. Table 4 shows that the correlation between these two variables is generally very high. Omitting two cases, the average coefficient of determination (r^2) is .90. Thus, the results suggest that a logistic function can represent the data reasonably well.

Second, we test whether V_i conforms to equation (7). Using equation (10), we obtained least-squares estimates of V_i (after weighting the observations appropriately).[26/] Assuming that the errors in these estimates are uncorrelated with Π_i, L_i, S_i, and C_i, we have

$$\hat{V}_i \;=\; c_1 + c_2\,\Pi_i + c_3 L_i + c_4 S_i + c_5 C_i + \epsilon_i'\ , \tag{11}$$

Table 3 -- Estimates of L_i, S_i, C_i, M_i, Q_i, K_i, and A_i .

Railroad	a/ L_i	b/ S_i	c/ C_i	d/ M_i	e/ Q_i	e/ K_i	e/ A_i
Pennsylvania	7	54.3	1.68	94	243	4.1	2300
New York Central	7	38.9	1.55	90	237	3.4	1720
Baltimore and Ohio	7	25.3	1.61	95	221	4.5	990
Illinois Central	9	18.7	1.68	92	275	8.3	620
Burlington	3	18.5	1.29	95	309	8.7	690
Missouri Pacific	6	21.2	2.55	97	295	4.9	910
Great Northern	3	16.3	1.44	93	287	6.5	580
Rock Island	0	12.8	2.35	88	312	3.3	400
Northern Pacific	4	11.6	1.98	89	394	4.8	510
Lehigh Valley	2	4.3	1.45	90	191	6.0	180
Nickel Plate	6	9.4	1.73	76	243	5.5	340
Lackawanna	4	4.1	2.17	80	162	2.3	180
Boston and Maine	3	3.1	1.44	96	157	5.2	220
Chicago and Eastern Illinois	5	1.6	1.93	100	193	3.1	60
Duluth,Missabe,and Iron Range	12	3.2	.88	81	76	27.7	130
Denver and Rio Grande	1	5.0	1.31	83	284	5.1	210
Bessemer and Lake Erie	9	2.1	1.98	51	108	6.8	80
Western Pacific	1	3.2	2.37	79	458	4.7	140
Monon	4	1.0	5.52	100	166	5.0	40
Florida East Coast	4	0.8	2.42	100	226	5.3	80
Maine Central	5	0.9	1.46	99	120	4.1	60
Pittsburgh and West Virginia	6	0.4	2.21	62	62	2.1	20
Kansas,Oklahoma, and Gulf	8	0.5	1.71	90	126	5.0	10
Seaboard Air Line	2	7.9	2.61	86	217	10.2	40
Virginian	13	3.2	1.92	50	248	7.9	40
Chesapeake and Ohio	8	27.0	1.26	76	276	5.7	780
Chicago and North Western	4	12.4	1.54	99	180	6.9	510
Norfolk and Western	16	15.3	1.96	65	275	7.2	460
Missouri-Kansas-Texas	6	5.1	1.35	100	303	3.1	190
Union Pacific	4	29.0	2.28	84	559	7.9	1040

Source: Statistics of Railways [10], and Moody's Railroads.

a/ To measure L_i, we obtained from the Statistics of Railways [10] the year when each firm's diesel locomotives first reached 10 percent of its total locomotive stock, and we deducted 1941 (the year when diesel locomotives reached 10 percent of the total locomotive stock on the first American railroad) from it.

b/ The number of freight ton-miles (in billions) in 1949 (obtained from the Statistics of Railways [10]).

c/ The average of the current ratio in the year prior to and the year when diesel locomotives first reached 10 percent of the firm's total locomotive stock.

d/ The percentage of a firm's steam locomotives that were 15 years old or more at the time when diesel locomotives first reached 10 percent of the firm's total locomotive stock.

e/ See Section 6 for a definition of Q_i, K_i, and A_i .

Table 4 -- Estimates of α'_i, V_i, Coefficient of Determination, and H_i .

Railroad	$\hat{\alpha}'_i$	$\hat{V}_i$	Coefficient of Determination [a/]	$\hat{H}_i$ [b/]
Pennsylvania	- 7.48	.43	.92	.73
New York Central	- 5.95	.35	.91	.88
Baltimore and Ohio	- 6.10	.34	.98	-
Illinois Central	- 6.21	.30	.92	-
Burlington	- 4.80	.29	.99	.49
Missouri Pacific	- 6.94	.44	.99	.73
Great Northern	- 4.44	.27	.95	.49
Rock Island	- 4.32	.29	.87	.63
Northern Pacific	- 5.20	.27	.89	-
Lehigh Valley	- 4.72	.33	.79	.88
Nickel Plate	- 6.47	.34	.93	-
Lackawanna	- 4.20	.28	.90	.73
Boston and Maine	- 5.01	.33	.94	.63
Chicago and Eastern Illinois	- 5.93	.40	.73	2.20
Duluth,Missabe,and Iron Range	-9.39	.40	.71	-
Denver and Rio Grande	- 3.96	.25	.93	.44
Bessemer and Lake Erie	- 7.18	.41	.74	-
Western Pacific	- 4.79	.36	.87	.63
Monon	-11.97	1.04	.84	2.93
Florida East Coast	- 5.52	.35	.91	-
Maine Central	- 6.91	.45	.95	1.10
Pittsburgh and West Virginia	- 8.50	.51	.85	1.10
Kansas,Oklahoma,and Gulf	-11.74	.73	.45	1.46
Seaboard Air Line	- 5.28	.36	.97	.55
Virginian	-15.32	.75	.57	-
Chesapeake and Ohio	-10.30	.59	.88	.88
Chicago and North Western	- 5.80	.33	.99	.88
Norfolk and Western	-30.48	1.35	.98	-
Missouri-Kansas-Texas	-11.16	.73	.94	1.25
Union Pacific	- 5.58	.33	.97	-

Source: *Statistics of Railways* [10], 1925-56 and additional ICC data described in note 32.

a/ The square of the coefficient of correlation between $\ell n\, [P_i(t)/1-P_i(t)]$ and t , the observations being weighted as Berkson [2] has suggested. As Griliches [8] pointed out, high correlation coefficients of this sort should be taken with a grain of salt. Nonetheless, the fits seem on inspection to be reasonably good in almost all cases.

b/ See Section 7 (and note 32 in particular) for a definition of $\hat{H}_i$ and a description of how it was obtained.

where $\hat{V}_i$ is the estimate of V_i and ϵ'_i is an error term. Using least-squares to estimate the c's, inserting these estimates into equation (8), and suppressing ϵ'_i, we have

$$(12) \qquad \hat{V}_i = -.163 + \underset{(.492)}{.900}\,\Pi_i + \underset{(.008)}{.048}\,L_i - \underset{(.0023)}{.0028}\,S_i + \underset{(.040)}{.115}\,C_i ,$$

where the quantities in parentheses are standard errors.

The results are quite encouraging. The estimates of c_2, c_3, c_4, and c_5 turn out to have the expected signs, and all but c_4 are statistically significant (.05 level). About 70 percent of the observed variation in $\hat{V}_i$ can be explained by the regression, the correlation coefficient being .83. Thus, the model, simple and incomplete though it is, can explain a substantial portion of the interfirm variation in the intrafirm rates of diffusion.

A convenient measure of the effect of each of the exogenous variables on the rate of intrafirm imitation is the elasticity of the time interval in Table 2 (between the dates when a firm was 10 percent and 90 percent dieselized) with respect to the exogenous variable. The estimated elasticities are $-.35$ (Π_i), $-.60$ (L_i), $.07$(S_i), and $-.49$ (C_i). All are evaluated at the means of the exogenous variables. Judging by these results, the intrafirm rate of diffusion is most sensitive (in an elasticity sense) to changes in L_i and least sensitive to changes in S_i.[27]

6. Effect of Additional Factors

Some of the important factors that help to account for the unexplained variation in $\hat{V}_i$ seem fairly obvious. The intrafirm rate of diffusion was probably affected by the amount of pressure exerted on the firm by the diesel locomotive manufacturers. It was probably affected too by the training and preference regarding risk of the firm's technical officers and top management. Moreover, changes over time in the profitability of the firm's investment in diesel locomotives undoubtedly was a significant factor. Although these factors were probably important, they were omitted because no satisfactory way could be found to measure them.[28/]

In this section, we investigate the effects of four additional variables that may have been important and that can be measured at least roughly. The first factor is the age distribution of the steam locomotives owned by the i^{th} firm when it "began" to dieselize. Assuming that this age distribution was rectangular with its upper end point at the replacement age, the percent of a firm's locomotives that had to be replaced each year after it "began" to dieselize was inversely related to the range of this distribution. Moreover, the range was inversely related to M_i -- the percent of the i^{th} firm's steam locomotives that were 15 years old or more when it "began" to dieselize. Thus, since the intrafirm rate of diffusion would be expected to vary directly with the percent of a firm's steam locomotives that were due for replacement each year after it "began" to dieselize, one would expect $\hat{V}_i$ to be directly related to M_i . To check this, M_i was included as an additional independent variable in equation (12), the result being

$$\hat{V}_i = -.257 + \underset{(.515)}{.849}\,\Pi_i + \underset{(.009)}{.051}\,L_i - \underset{(.0023)}{.0030}\,S_i + \underset{(.041)}{.117}\,C_i + \underset{(.0025)}{.0011}\,M_i \quad . \tag{13}$$

The regression coefficient for M_i has the right sign, but is statistically non-significant.[29]

The second factor is A_i, the absolute number of diesel locomotives that the i^{th} firm had to acquire in order to go from 10 to 90 percent of full dieselization. As this number increases, the firm is forced to invest more heavily each year in diesel locomotives in order to make this transition in a given length of time (and hence to maintain a given value of V_i). Since it may not be possible or worthwhile for firms of given size to support an annual investment exceeding some maximum amount, V_i may be inversely related to this number. To check this, A_i was included in equation (12), the result being

$$\hat{V}_i = -.174 + \underset{(.490)}{1.036}\,\Pi_i + \underset{(.008)}{.047}\,L_i + \underset{(.0118)}{.0126}\,S_i + \underset{(.040)}{.108}\,C_i - \underset{(.00028)}{.00038}\,A_i \quad . \tag{14}$$

The regression coefficient for A_i has the right sign, but is statistically non-significant.[30]

The third factor is the average length of haul of the i^{th} firm. Diesel locomotives would be expected to be particularly profitable for railroads that made long hauls, because intermediate service points could be eliminated. Thus, one might expect V_i to be directly related to Q_i -- the i^{th} firm's average length of haul (in miles) during 1937-46. But when this variable is added to equation (12), we find once again that, although the sign of its regression coefficient is "right," the coefficient is not statistically significant. More specifically, the result is

$$(15) \qquad \hat{V}_i = -.268 + \underset{(.500)}{1.058}\, \Pi_i + \underset{(.008)}{.052}\, L_i - \underset{(.0025)}{.0043}\, S_i + \underset{(.040)}{.106}\, C_i + \underset{(.00031)}{.00039}\, Q_i \, .$$

The fourth factor is the profitability of the i^{th} firm. More profitable firms might be expected to have higher value of V_i because they were better able than other firms to finance the necessary investment and to take risks. To check this, K_i -- the average ratio of the i^{th} firm's railway operating revenue to its total adjusted capital in the two years prior to and including the year when it "began" to dieselize -- is included as an additional independent variable in equation (12), the result being

$$(16) \qquad \hat{V}_i = -.087 + \underset{(.520)}{.692}\, \Pi_i + \underset{(.008)}{.052}\, L_i - \underset{(.0023)}{.0032}\, S_i + \underset{(.040)}{.113}\, C_i - \underset{(.0073)}{.0086}\, K_i \, .$$

The regression coefficient for K_i has the wrong sign and is statistically non-significant.[31]

Thus, although M_i, A_i, Q_i, and K_i might be expected to influence V_i in the ways we describe, there is no real evidence that they exerted such an influence. Their apparent effect is almost always in the expected direction, but it is statistically non-significant in every case.

7. Results Based on Utilization Data for Freight Service

Our measure of the rate of intrafirm diffusion is based on the number of locomotive units of each type (steam and diesel) owned by a firm. This measure suffers from the fact that locomotives differ in size and capacity and that some locomotives may be used little (if at all). It also suffers from the fact that freight, passenger, and switching service have to be lumped together. It would be preferable to use a measure based on the growth over time in the percent of total work done by diesels and to separate various types of service, but only a small amount of data of this sort has been published.

Using the available data regarding freight service (perhaps the most significant type of work), we try to determine whether our findings would have been modified substantially if utilization data of this sort, rather than ownership data, had been used. The model in Section 4 can easily be modified to accommodate such data. Let N_i' be the total freight ton-miles of the i^{th} firm during the relevant period, $D_i'(t)$ be the number of freight ton-miles hauled by diesels at time t, and

$$\begin{aligned} W_i'(t) &= \Big[D_i'(t+1) - D_i'(t)]/[N_i - D_i(t)\Big] . \\ &= g[\Pi_i, U_i(t), S_i\ C_i, \ldots] . \end{aligned}$$

Proceeding as we did in Section 4 and letting $P_i'(t)$ be the proportion of the i^{th} firm's total freight ton-miles hauled by diesels at time t, we find that

$$P_i'(t) = \left[1 + e^{-(\beta_i + H_i t)}\right]^{-1} ,$$

$$H_i = d_1 + d_2 \Pi_i + d_3 L_i + d_4 S_i + d_5 C_i + e_i'' ,$$

where e_i'' is an error term.

From published ICC data, it is possible to piece together enough information regarding $P_i'(t)$ to allow a rough test of this model for twenty of the firms in Table 3. Apparently a logistic function provides a reasonably good fit. Using the rough estimates of H_i shown in Table 4 (and omitting e_i''), we find that

$$(17) \qquad \hat{H}_i = -.268 + \underset{(1.732)}{.502}\, \Pi_i + \underset{(.040)}{.138}\, L_i - \underset{(.007)}{.016}\, S_i + \underset{(.114)}{.391}\, C_i ,$$

the coefficient of correlation being .83. When M_i, A_i, Q_i, and K_i are inserted into equation (17) as additional independent variables, the results are generally like those in the previous section, the only notable difference being that the effect of M_i is statistically significant.[32]

Thus these fragmentary data regarding the utilization of diesels in freight service yield the same general kind of results as those obtained from ownership data. The effects of Π_i, L_i, S_i, C_i, and M_i are in the same direction, and the model in Section 3 seems to fit about as well in one case as in the other. The only difference is that some coefficients are statistically significant in one case but not in the other, the effects of M_i and S_i being significant here (but not in Sections 5-6) and the effect of Π_i being non-significant here (but significant in Sections 5-6).

8. Summary and Conclusions

Once a firm begins using a new type of equipment, what determines how rapidly it substitutes it for older types? To help answer this question, we constructed a simple model to explain how rapidly, once a firm began to dieselize, it substituted diesel motive power for steam. When tested against data for 30 Class I railroads, this model seemed to stand up quite well. About 70 percent of the interfirm variation in the rate of dieselization could be explained, and the effect of each exogenous variable was in the expected direction and (with one exception)[33/] statistically significant. Although the model is obviously over-simplified and incomplete, it is of considerable help in explaining the substantial differences among the intrafirm rates of diffusion of this innovation.

Since these findings pertain to only one innovation, they provide little information regarding the usefulness of a model of this sort for new techniques in general. However, judging from what little additional evidence we have, there seems to be a good chance that the same sort of model would be useful in dealing with a wide class of innovations.[34/] If so, this would have at least four implications.

First, it would mean that the same sort of model can be used to represent both the rate of diffusion among firms and the rate of diffusion within a firm. The model used here emphasizes the same sorts of explanatory factors and is similar in structure to one used with considerable success in [12] to represent the rate of interfirm diffusion of an innovation. The fact that the same sort of model works reasonably well in both cases suggests that there is a considerable amount of unity and similarity between the two diffusion processes. Moreover, the results in each case lend support to those in the other case.

Second, together with previous results, it would suggest that there exists an important economic analogue to the classic psychological laws relating reaction time to the intensity of the stimulus.[35] The profitability of an investment opportunity acts as a stimulus, the intensity of which seems to govern quite closely a firm's speed of response. In terms of the diffusion process, it governs both how rapidly a firm begins using an innovation and how rapidly it substitutes it for older methods.

Third, if the effect of a firm's size is generally like that found here, it would be of considerable interest to economists concerned with problems regarding industrial concentration and the large firm. In line with the allegations of Stocking [17], Yance [20], and others, it would appear that small firms, once they begin, are at least as quick to substitute new techniques for old as their larger rivals. Although this is obviously only one of a great many considerations in formulating policy in this area, it is worthy of attention.[36]

Fourth, the results point up the importance in this regard of when a firm begins to use the innovation, the age of its equipment at that time, and its liquidity. All of these factors have a statistically significant effect on the intrafirm rate of diffusion, (measured in terms of either the ownership or the utilization data or both).[37] However, as so often has been the case in studies of investment behavior, the effect of the profitability of the firm is not statistically significant.

In conclusion, further efforts should be made, using data for other innovations, to test this sort of model of the intrafirm rate of diffusion of an innovation. Moreover, studies should be made of how a firm's rate of diffusion varies among innovations. Studies of the latter kind would provide an important supplement to investigations like this (of interfirm differences in the rate of diffusion of the same innovation) because they can gauge more adequately the impact of factors like the durability of old equipment, the investment required to introduce the innovation, and the business cycle. It is important that we understand more fully the factors determining how rapidly a firm substitutes a new technique for older ones, and studies of both sorts can make an important contribution toward this end.

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FOOTNOTES

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1/ It seems obvious that productivity in an industry can be regarded as a weighted average of the productivity with the old technique and the productivity with the new, the weights reflecting the extent to which the new technique has replaced the old. (Whether one has in mind labor, capital, or total productivity is irrelevant, although it affects the sort of weights one would use.) Thus, if the productivity with the new technique exceeds that with the old, productivity in the industry will rise as the new technique is substituted for the old. The rate at which it rises depends clearly on the rate of diffusion. And if the diffusion process goes on more slowly than it should, productivity will not rise sufficiently rapidly and output will fall below its potential. (Of course if the diffusion process goes on too rapidly, inefficiencies result as well.) For further discussion, see Salter [16].

2/ Note that the intrafirm rate of diffusion measures how quickly a firm substitutes the new technique for the old <u>once it has begun to use the technique</u>. It does not tell us anything about the speed at which it began to use it. See Section 3. Note too that some innovations can only be introduced on such a large scale that the intrafirm rate of diffusion is of little relevance. The firm either adopts the innovation or it does not. In addition, we presume here that there is an old technique that the innovation replaces.

Assuming that the new technique will completely displace the old, a reasonable, but arbitrary, measure of the intrafirm rate of diffusion is the time interval separating the date when the innovation accounts for 10 percent of the firm's output from the date when it accounts for 90 percent of the firm's output. This sort of measure (which is inversely related to the intrafirm rate of diffusion) is used in Section 3. If the new technique will eventually displace the old in B percent of the cases, .1B and .9B can be used instead of 10 and 90.

Studies of the diffusion process are relatively rare for industries other than agriculture. For some studies bearing on the spread of innovations among industrial firms, see Enos [6], Healy [9], Mansfield [12, 13, 15], and Sutherland [18]. For some investigations of agricultural innovations, see Beal and Bohlin [1] and Griliches [8]. For the diffusion of an antibiotic, see Coleman, Katz, and Menzel [4].

Some attention was devoted to the diesel locomotive by Healy [9]. Moreover, Yance did some unpublished work [20] on this innovation. But most of their work pertained to the spread of the diesel locomotive among firms, not to the intrafirm rates of diffusion. Thus, the amount of overlap with the present study is relatively small.

3/ Given that one knows the percent of the firms in the industry that have begun to use the innovation at each point in time and the average percent of output produced with the innovation (or some similar measure of the intrafirm rate of diffusion) by these firms at each point in time, one can simply multiply them to get the corresponding measure of the rate of diffusion in the industry (if the firms are roughly of the same size). The rate at which firms begin to use an innovation is studied in [12], and the factors determining whether one firm will be quicker than another to begin using it is studied in [13]. Thus, the combined results of these previous papers and the present one should help to explain the rate of diffusion in the entire industry.

4/ During the Twenties, diesel locomotives were employed in a limited way in many countries, their most extensive use being in places lacking coal supplies. The first operational diesel locomotive made in the United States resulted from the joint efforts of Ingersoll-Rand (which built the engine), General Electric (which made the components), and American Locomotive (which made the structure). It was put in demonstrating service on June 9, 1924 in New York. It was used for demonstration purposes for eighteen months and then was used by Ingersoll-Rand for experimental and development purposes. This sixty-ton unit was equipped with one 300 h.p., 200 k.w. oil engine generator set. Railway Review (May 8, 1926).

5/ When municipal governments put pressure on the railroads to eliminate the smoke nuisance, they sometimes turned to diesel power because it was cheaper than electrification. For a sketch of the early history of the diesel locomotive outside the United States, and for references to more detailed accounts, see Jewkes, Sawers, and Stillerman [11]. For a sketch of its early history in this country, see Healy [9], Jewkes, Sawers, and Stillerman [11], and Yance [20]. For a "biography" of one of the earliest diesel locomotives, see Trains (November 1956), pp. 26-28.

6/ For a description of the GM locomotive and some early comparisons of the cost of diesels and steam locomotives, see Foell and Thompson [7].

7/ There is a definite relationship between (1) how rapidly a firm began using diesels and (2) its size and the percent of its revenue obtained from hauling coal. Using only these two independent variables, the coefficient of correlation for all Class I railroads is .70. See Mansfield [13].

8/ Letters were sent to the presidents of most of the railroads included in the sample in Table 3. These letters asked various questions regarding the firms' acceptance of the diesel locomotive. About two-thirds of the railroad presidents replied.

One question was: when were diesel locomotives no longer considered experimental by your firm? A percentage breakdown of the replies is: before 1932, none; 1932-35, 23%; 1936-39, 23%; 1940-43, 39%; 1943-45, 15% . This pertains only to switchers. Road locomotives generally remained in the experimental stage several years longer.

Of course, some of the variation here may be due to differences in the interpretation of "experimental." For a summary of some of the other data obtained in this way, see notes 9 and 11.

9/ According to the correspondence cited in note 8, most diesel locomotives introduced before World War II were used for switching. Only about 15% of the responding firms used them for any work other than switching at that time.

In the course of other correspondence with the firms listed in Table 3, each firm was asked to estimate the average pay-out period for diesel locomotives introduced prior to World War II. About half of the firms replied. The unweighted average of the estimates obtained was 6 years. Of course, there was substantial variation of the estimates by individual firms about this average. For comments on the data, see Mansfield [12].

10/ According to the president of a major Eastern road it became much easier for the railroads to obtain diesel locomotives after May 1943.

11/ For eleven of the seventeen firms, we received complete data on Y_1, the year when plans for complete dieselization were first drawn up, Y_2, the year when these plans visualized that complete dieselization would be accomplished, and Y_3 the year when in fact it was accomplished. These data follow:

Railroad	Y_1	Y_2	Y_3
1	1951	1954	1954
2	1950	1953	1953
3	1945	1955	1955
4	1945	1955	1953
5	1945	1955	1953
6	1954	1959	1960
7	1945	1955	1956
8	1954	1958	1957
9	1947	1958	1955
10	1946	1956	1956
11	1947	1961	1958

12/ In the 1920's and early 1930's, the smallest diesel switchers cost about $100,000. By 1936, a 1000 h.p. diesel switcher cost about $100,000 and a large steam switcher cost about $70,000. By 1948, a 1000 h.p. diesel switcher still cost about $100,000 but a large steam switcher cost about $120,000. See Healy [9], p. 175.

13/ Diesel manufacturers helped firms choose the most profitable installations, determine rates of return, and set up schedules. They helped to train operating and maintenance personnel. One manufacturer conducted a service where firms submitted cost data on a confidential basis and received summaries of corresponding data from other firms in return. See Yance [20].

14/ A comparison of Y_2 with Y_3 (in note 11) suggests that these programs were generally completed on time.

15/ Throughout this paper, the year when a firm "began" to dieselize will mean the year when diesel locomotives first reached 10 percent of its total locomotive stock. When the quotation marks are omitted, it will mean the year when the first diesel locomotive was purchased.

16/ Three further points might be noted. (1) For discussions showing the relevance of the sort of measure used in Table 2 (rather than the rate at which diesels came to dominate locomotive purchases) to changes over time in productivity, see note 1 and Salter [16]. Of course we concentrate entirely on differences in productivity between diesel and steam locomotives and ignore the variation in productivity among locomotives of each type. (2) Little or nothing can be deduced from Table 2 regarding the rate at which diesel locomotives came to dominate new orders. (3) Another measure of the intrafirm rate of diffusion, V_i, is used in the following section. This measure has the advantage that it does not rely on any arbitrary percentages like 10 and 90. For any P_1 and P_2, if the model holds, V_i is inversely proportional to the time interval separating the date when diesels were P_1 percent of the total from the date when they were P_2 percent of the total. Results based on V_i also indicate that there were large differences in the intrafirm rates of diffusion.

17/ If we are interested primarily in how rapidly a firm went from 10 to 90 percent of full dieselization, it is only important that our model hold for the postwar period. If it does not hold so well for earlier times, the result will only be that it will not explain the movement up to about 10 percent very well.

18/ The assumption that each firm's traffic volume (and motive power requirements) remained constant over time is only a convenient approximation, but during the late Forties and early Fifties (when dieselization was going on at a significant pace) there was little or no trend in railroad traffic. Letting 1929 = 100, the index of railroad output was 144 in 1946 and 136 in 1956.

On many railroads, there may have been a tendency for R_i to decrease with time. But for most of the relevant period, the decrease was probably slight.

19/ Of course, one might also reason that, because larger firms were better able to finance the investment and take risks, the effects of S_i might be in the opposite direction from that supposed in the test. Originally, I thought that this might be the case but further research has convinced me otherwise.

Of course, a larger investment in diesel locomotives between time t and time $t+1$ does not necessarily result in a higher value of $W_i(t)$. One can only be sure that this will be the case if N_i/R_i and $R_iD_i(t)/N_i$ are held constant, since under these circumstances the number of places left to be filled with diesel locomotives at time t will be constant. Thus, N_i/R_i and $R_iD_i(t)/N_i$ may be two of the factors influencing $W_i(t)$ that are omitted from equation (3). In the analysis below, both are introduced explicitly (N_i/R_i being closely related to A_i).

20/ The reasoning here is as follows. $U_i(t)$ is identically equal to the product of $U_i(t_i^*)$ and $U_i(t)/U_i(t_i^*)$, where t_i^* is the year when the i^{th} firm "began" to use diesel locomotives. We assume that $U_i(t_i^*)$ is inversely related to L_i and that $U_i(t)/U_i(t_i^*)$ is inversely related to $R_iD_i(t)/N_i$. Thus, $U_i(t)$ is inversely related to L_i and $R_iD_i(t)/N_i$. These assumptions seem reasonable (and the data below bear them out) but their roughness should be obvious, and somewhat different measures might have been used. For example, we might have used $D_i(t)$ rather than $R_iD_i(t)/N_i$, but the latter seems to work quite well.

21/ Descriptions of these interviews are contained in Mansfield [12, 13]. Coleman, et al., [4] present evidence regarding the diffusion of an antibiotic that tends to support the hypothesis that $W_i(t)$ is directly related to L_i. Griliches [8] presents evidence regarding hybrid corn that tends to support the hypothesis that $W_i(t)$ is directly related to Π_i. Yance [20] presents evidence that tends to support the hypothesis that $W_i(t)$ is directly related to $R_iD_i(t)/N_i$. Mansfield [12, 13] presents evidence regarding a dozen innovations that bears on several of these hypotheses.

With regard to the effects of C_i, note too that about half of the respondents to the letters described in note 8 emphasized that the financial condition of the firm was an important determinant of the rate of diffusion of the diesel locomotive. Unfortunately, it is difficult to know precisely what they meant by "financial condition" and how this can be measured. However, from the remarks, it seemed that the liquidity of the firm was closely linked with their notion of "financial condition."

22/ See [12], Section 3.

23/ Of course, it would have been preferable to have studied the growth over time in the percent of total traffic hauled by diesel locomotives rather than the percent of the locomotive stock that are diesels. I used the latter measure because it was the only one that was published on a firm-by-firm basis. Section 7 analyzes what little data are available regarding the growths over time in the percent of freight "output produced" by diesel locomotives.

Note too that, if the model holds, there is a simple relationship between V_i and the figure for the i^{th} firm in Table 2. The latter equals $4.39/V_i$.

24/ An entire system is regarded as a single railroad here.

25/ Each firm in Table 3 was asked to estimate the average pay-out period for the diesel locomotives it bought during 1946-57. The reciprocal of this pay-out period (which is a crude estimate of the rate of return) is used as an estimate of Π_i for the 22 firms that replied.

For the others, we estimated Π_i in the following way. First, we estimated R_i (except for a multiplicative constant) for all 30 firms. To obtain this estimate, we assumed that all railroads were working at $100\,\Phi$ percent of "capacity" in 1939 and at $100\,\Theta$ percent of "capacity" in 1957. Thus, if the i^{th} firm hauled t_i^0 ton-miles of freight in 1939 and had Z_i^0 locomotives in 1939 (practically all steam), $\Phi Z_i^0/t_i^0$ steam locomotives were required per ton-mile of freight on this road. Similarly, if the i^{th} firm hauled t_i^1 ton-miles of freight in 1957 and had Z_i^1 locomotives in 1957 (practically all diesels), $\Theta Z_i^1/t_i^1$ diesel locomotives were required per ton-mile of freight on this road. Thus, one diesel locomotive can replace $\Phi Z_i^0\, t_i^1/\Theta Z_i^1\, t_i^0$ steam locomotives. As a measure of R_i, we use $Z_i^0\, t_i^1/Z_i^1 t_i^0$ -- which was proportional to R_i if these assumptions hold. Of course this is very crude. Freight ton-miles are not a completely adequate measure of a firm's output. All firms may not have been operating at approximately the same percentage of "capacity." A firm's "capacity" may not be a linear, homogeneous function of the number of locomotives it owned. The resulting measures of R_i are only rough approximations.

Second, we found that our estimate of Π_i was correlated with our estimate of R_i for the 22 firms where data on Π_i were available. According to the interviews, such a relationship would be expected. Using the regression of Π_i on R_i, we estimated the value of Π_i for the remaining 8 firms on the basis of their value of R_i.

Note that we assume that the interfirm differences in the profitability of introducing diesel locomotives were approximately the same over time. Variation over time during the relevant period is ignored. There is some evidence that the diesel locomotives introduced after the war were somewhat less profitable than those introduced before and during it (although the very last stages of dieselization were often the most profitable). Estimates of the pay-out period (like those in note 9) obtained for the post-war period tended to be somewhat higher than those in note 9.

26/ Berkson's [2] weights are applied. Only those values of t such that $.01 \leq P_i(t) < 1$ are included, and t is measured in years from 1939.

27/ According to the model, the interval in Table 2 equals $4.39/V_i$, which is approximately $4.39\,[c_1 + c_2\,\Pi_i + c_3\,L_i + c_4\,S_i + c_5\,C_i]^{-1}$. Thus, letting I represent this interval, $\frac{dI}{d\Pi_i} \cdot \frac{\Pi_i}{I} = - c_2\,\Pi_i\,[c_1 + c_2\,\Pi_i + c_3\,L_i + c_4\,S_i + c_5\,C_i]^{-1}$. Similar results are obtained for L_i, S_i, and C_i. Evaluating the results at the means of the exogenous variables, we get the numbers in the text.

28/ In the current anti-trust case brought against General Motors, one of the points at issue seems to be whether or not it exerted undue influence on the railroads. See Business Week (April 15, 1961). For what it is worth, the interviews (see note 21) indicated that reciprocity was often an important factor here.

Of course, another factor that might be important here is a firm's rate of growth -- because of its impact on the extent of a firm's investment in new locomotives and the rate at which old locomotives are scrapped. Although we assume throughout that every firm's output remains the same throughout the period, this is only a convenient first approximation.

Salter [16] describes a number of factors influencing the rate of diffusion, but his analysis cannot easily be applied here because the railroad industry is regulated. His analysis is concerned primarily with free markets. Another relevant publication is Terborgh [19].

29/ We assume that each firm's steam locomotives were replaced when they were X years old (the diesel being available as an alternative) and that the age distribution of each firm's steam locomotives was rectangular when it "began" to dieselize, the upper end-point of the distribution being X . If so, the lower end-point must equal $\chi - (\chi - 15)/M_i$, and the range of the distribution (a measure of the amount of variation) must equal $(\chi - 15)/M_i$. Moreover, since the proportion of a firm's steam locomotives that had to be replaced each year immediately after it "began" to dieselize is the reciprocal of the range of the distribution, this proportion is directly related to M_i . Finally, one would expect the intrafirm rate of diffusion to be directly related to this proportion because, as the proportion of steam locomotives falling due for replacement each year increases, the minimum time required to attain full dieselization decreases.

Of course, the assumption that the age distribution can be approximated by a rectangular distribution and that its maximum was X (which was the same for all firms) is very rough. Moreover, the minimum and actual time required to attain full dieselization may not be very closely related. These factors may explain the non-significant results in equation (13). Moreover it is possible that the results would have been different if some cut-off point other than 15 years had been used. (The form of the basic data required that we use a measure like M_i to estimate the range.) Certainly, the present analysis of the effect of the age distribution of steam locomotives on the intrafirm rate of diffusion is only a beginning.

Finally, we fit this factor into the model simply by adding M_i to the list of variables on the right-hand side of equation (3) and treating it like the other variables in subsequent equations. The result is that $\hat{V}_i$ should be a linear function of it too. (The same procedure is used in dealing with the other factors in this section.) But under some circumstances, it is difficult to fit M_i into this framework because its effects on $W_i(t)$ are likely after a while to change with time. This problem does not arise so acutely with the other three factors discussed in this section.

30/ Note that, when A_i is included in the regression, the regression coefficient for S_i becomes positive. Of course, this is because A_i and S_i are highly correlated.

31/ Of course, this result may be due to inadequacies in the data regarding K_i. For example, the time periods to which these data pertain are somewhat arbitrary. Note too that this result is quite consistent with Eisner's findings [5] regarding the investment function.

32/ For 1951-1954, we could obtain the percent of freight ton-miles hauled by diesel locomotives for 23 of the firms in Table 4. These figures came from the ICC's Monthly Comment on Transport Statistics (1951, 1952, and 1953) and Moody's. Prior to 1951 we could obtain the percent of freight locomotive miles accounted for by diesel locomotives for all the firms. These figures came from the ICC's Comparative Statement of Railway Operating Statistics. Ignoring the differences between these two measures, we computed the time interval between the date when the percentage equaled 10 and the date when it equaled 90. Then we divided this interval into 4.39 to obtain a rough estimate of H_i. Such an estimate could be made for only 20 firms since not all firms had reached 90 percent by 1954. See Table 4. These seem to be the only published data that are available.

Of course, to be consistent, we should probably have based our measure of L_i, C_i, M_i, and K_i on the date when diesel locomotives accounted for 10 percent of freight ton-miles rather than 10 percent of the locomotive stock. But it is doubtful that this would have made any appreciable difference.

When M_i is added to equation (17), the result is $\hat{H}_i = -1.76 - \underset{(1.572)}{.114}\,\Pi_i + \underset{(.036)}{.136}\,L_i - \underset{(.006)}{.017}\,S_i + \underset{(.100)}{.395}\,C_i + \underset{(.008)}{.018}\,M_i$. The correlation coefficient is almost .9.

33/ See note 36.

34/ As we pointed out in note 21, the results from the studies previously made of the diffusion process seem to indicate that the factors considered here are important (and that they operate in the expected direction) for innovations of various sorts in a variety of industries.

35/ See for example [3]. Note that Π_i has a statistically significant effect only when the ownership, rather than the utilization, data are used. However, if utilization data for all 30 firms had been available, I strongly suspect that it would have had a significant effect in both cases.

36/ In this connection see [14]. Note that S_i has a statistically significant effect only when the utilization, rather than the ownership, data are used.

37/ M_i has a statistically significant effect only when the utilization, rather than the ownership, data are used.