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FUZZY FRONTIERS OF PRODUCTION:
EVIDENCE OF PERSISTENT INEFFICIENCY
IN SAFETY EXPENDITURES

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ABSTRACT

This study documents a strong inverse relationship between accident rates and production in a sample of eleven firms in the same narrowly defined industry classification. Given the detailed set of input controls and controls for plant-specific and time-specific factors used in the analysis, the study argues that a theoretical framework that describes firms as operating on well-defined production frontiers is not adequate for providing an entirely accurate interpretation of the basic empirical finding. Three elaborations to the basic production frontier framework are developed and used to interpret the accident-productivity relationship.

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I. INTRODUCTION

The basic construct of microeconomic theory used to describe a firm's operation is the production frontier. Simply, the production frontier maps the set of efficient input--output transformations with a given technology. Factor prices, then, will determine the position of competing firms on that frontier. In competitive markets, firms that err in short-run decisions will be forced out of the industry in the long run. Theoretical elaborations have of course been developed that permit competing firms to differ in their investments and their input configurations and still remain viable parts of the industry. There is, however, a very different tradition in microeconomics that questions the deterministic production frontier framework. Liebenstein's "x-inefficiency¹," Simon's "adaptive organizations²," and Cyert and March's "bounded-rationality" in their behavioral theory of the firm³ are leading examples of the view that competitive market forces do not insure microeconomic efficiency.

These two theoretical traditions provide very different frameworks for interpreting observed relationships between inputs and outputs. Unfortunately, empirical tests to distinguish between these views face formidable obstacles. Analysis of firm-level production would be required; however, accurate models of production at the micro-level are generally recognized to be much more difficult to develop than more aggregate forms. Even with an accurate functional form, micro data on plant operations are not publicly available. Difficulties with interpretation of any firm-level model will also exist. With the complexities of multiple input configurations in most production processes, it becomes virtually impossible to distinguish movements between frontiers from disturbances that force firms inside their frontiers. It is particularly difficult to

control for certain inputs such as investments in information and managerial ability. Others, who have estimated frontiers empirically and observe points inside the frontiers, consider such observations as evidence of a problem in one-sided measurement error.

To consider these important differences in theoretical interpretation, I analyze a unique set of data on the operations of eleven plants in the same four digit Standard Industrial Classification (SIC 2621-paper). The specific focus of the study is the relationship between plant safety and production after controlling for the effects of capital, labor, and energy. Several elaborations of the basic production frontier framework are developed and used to interpret the safety-productivity relationship. To evaluate each of the theoretical frameworks, I consider how reasonable each interpretation is given the nature of the empirical tests and the structure of control variables.

The study is developed in the four following sections. The next section describes the detailed model of the paper production process and the input-output data. Section III presents empirical estimates of the safety-productivity relationship obtained from the detailed model of production. Section IV presents the basic economic framework for considering the relationship between safety and production and introduces four elaborations on that framework. The empirical results obtained in Section III are interpreted within each of these theoretical frameworks. Finally, the conclusion considers the implications of broadening the basic production frontier framework to allow for a degree of persistent inefficiency in microeconomic production.

II. INPUT-OUTPUT DATA AND SPECIFICATION OF THE PRODUCTION PROCESS

Monthly observations from January 1976 to September 1982 on the operations of ten paper mills make up the sample for the study. With the aid of on-site investigations of each mill's production process, the production function given by equation 1 was developed to account for variations in productivity in these mills⁴:

$$\ln Q = \beta_0 + \sum_{i=1}^3 (\beta_{1i} \cdot KD_i) + \sum_{i=1}^9 (\beta_{2i} \cdot KV_i) + \sum_{i=1}^3 (\beta_{3i} \cdot PMD_i) + \sum_{i=1}^4 (\beta_{4i} \cdot PMV_i) + (\beta_5 \cdot L) + (\beta_6 \cdot E) + (\beta_7 \cdot AC) + \epsilon \quad (\text{Equation 1})$$

Where: Q = tons of physical output;

KD₁₋₃ = three plant dummies to control for two major product differences (white paper vs. newsprint; sheeted vs. not sheeted) and one major process difference (make vs. buy pulp) across the eleven mills;

KV₁₋₉ = total depreciated, deflated value of assets in nine distinct categories of assets;

PMD₁₋₃ = a set of three related dummy variables to describe whether a plant is operating two, three, four, or five or more paper machines (the two paper machine category is omitted);

PMV₁₋₄ = total depreciated, deflated value of the two, three, four or five plus paper machines;

L = labor input;

E = energy input;

AC = accident rate.

The KD variables provide a direct control for major product and process differences observed in these mills. The more conventional method of constructing a value added index is particularly difficult in these mills. The PMD variable provides some control over scale of operations. The KV and PMV variables are fashioned to recognize the principles of input aggregation for a heterogeneous capital stock. For example, three categories involving energy generation capital, certain land and buildings, and pollution and recycling capital are not a direct part of the machinery that acts upon the raw materials flowing through the process. These categories of capital are therefore kept separate from production process capital. The capital value variables are constructed from each mill's monthly asset inventory which contains information on the current value of each asset. In any month, there are some 15,000 assets that were allocated to these different categories of capital. L is defined as the natural logarithm of hourly manhours. A salaried manhours variable was unavailable for the analysis as was a more detailed breakdown of hourly manhours into its operating and maintenance labor components. E is the natural logarithm of BTU's used in production. AC, the Occupational Safety and Health Administration's (OSHA) accident rate, is described in detail below.

This unconventional specification is developed to provide an accurate model of production in these mills. Equation 1 accounts for over 95% of the total variation in production in this sample. More conventional functional forms produce several nonsensical coefficients. For example, in a Cobb-Douglas function,

the coefficient on capital is in fact negative for this set of plants in which capital plays the central role in transforming raw materials into final goods. More conventional forms explain a much smaller proportion of the total variation in output.⁵

After controlling for the effects of the principal inputs in this way, the partial correlation between the accident rate and production will be estimated. AC in equation 1 is the OSHA "all accident incident rate." It is defined as:

$$\frac{(\text{Doctor Cases} + \text{Lost Time Cases}) \bullet 200,000}{\text{Total hours worked} \bullet 100}$$

The mean of the accident rate variable across all mills is .071 with a standard deviation of .057. The lowest mill average is .056. The largest mill average is .099. 16.7% of all mill-months are accident free while the maximum value for this variable in this sample is .41.

III. EMPIRICAL RESULTS: ESTIMATES OF THE SAFETY-PRODUCTIVITY RELATIONSHIP

When equation 1 is estimated with the plant data, the coefficient on the accident rate variable shown in column 1 of Table 1 is obtained. The accident rate coefficient is $-.252$ and significant at conventional levels. Higher accident rates occur in periods of relatively low production. To understand the nature of this total effect better, the column 2 and 3 specifications are estimated. Column 2 gives the average within-plant effect. The capital dummies (KD_{1-3} in equation 1 which control for product and process differences across plants) serve as dummy variables for groups of plants. A complete set of ten plant dummies replaces the capital dummies to obtain the equation 2 specification. Again, the average within-mill relationship between accidents and production is significant and negative. In the column 3 specification, a set of time dummies is added to the column 1 equation to obtain an estimate of the cross-mill effect. To adjust for time trends and seasonal shifts in accidents or production, a set of six year dummies and a set of eleven month dummies are added. After controlling for time in this way, one finds that high accident rate mills are low production mills. The cross-plant accident rate coefficient in column 3 is slightly larger in absolute value than the column 1 coefficient, while the within-plant accident rate coefficient is slightly smaller in absolute value. All are significantly negative coefficients. Time dummies and plant dummies included, the accident rate coefficient given in column 4 is still significantly negative.

To provide a more intuitive understanding of the magnitude of these

Table 1: Accident Rate Coefficients in the Model
of Paper Production^a

[Dependent Variable: ln Tons of Paper; N = 545]

Independent Variables	Equation 1	Equation 2	Equation 3	Equation 4
1. accident rate	-.252*** (.108)	-.208*** (.100)	-.300** (.099)	-.232*** (.083)
2. capital dummies	yes	no	yes	no
3. plant dummies	no	yes	no	yes
4. time dummies	no	no	yes	yes
5. other capital value, energy, and hourly man-hours controls appearing in Table 5.1	yes	yes	yes	yes
R ²	.955	.962	.965	.969

a - standard errors in parentheses

*** - significant at the .01-level, one-tailed test

** - significant at the .05-level, one-tailed test

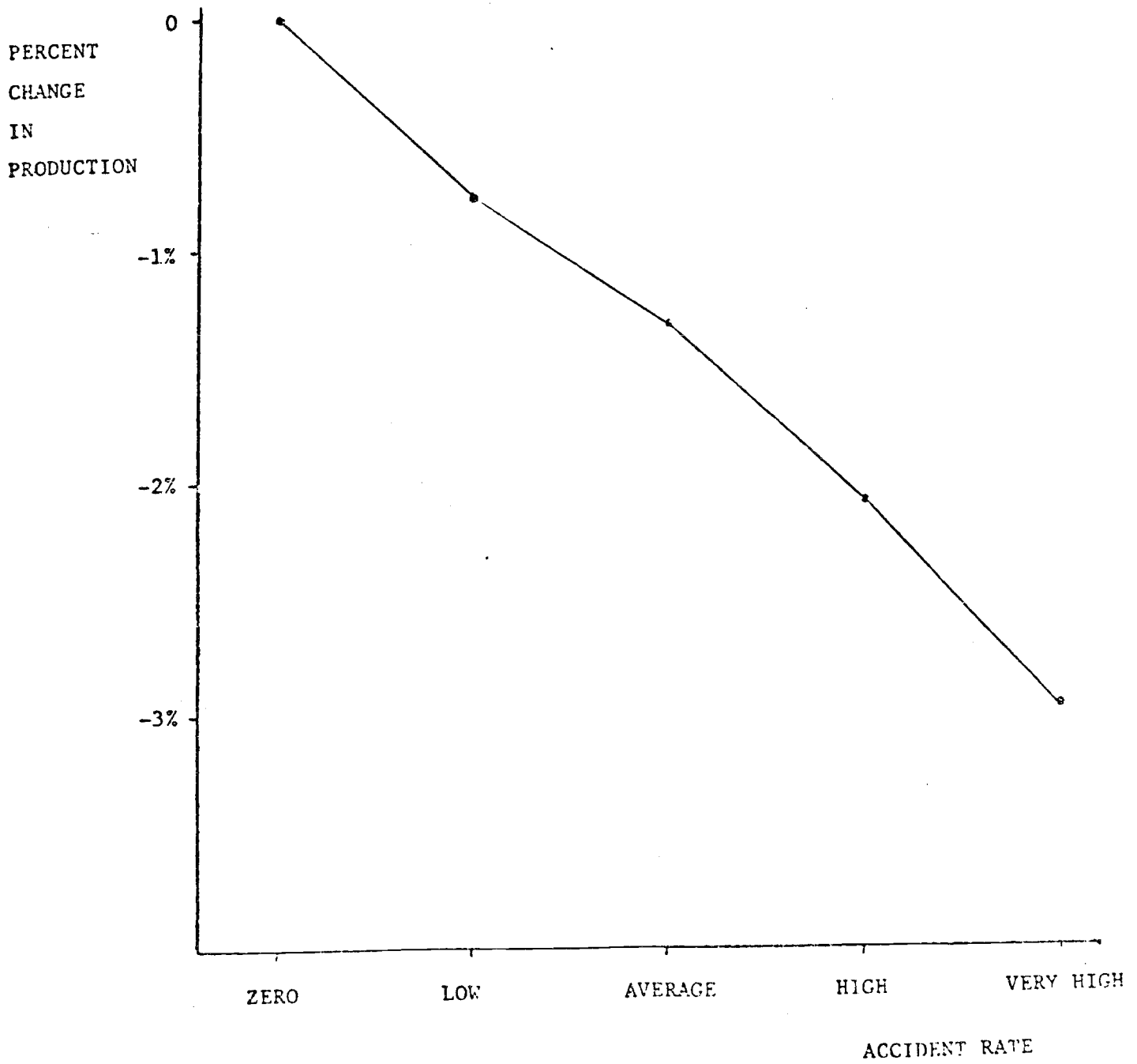
* - significant at the .10-level, one-tailed test

coefficients, the coefficient obtained in Column 2 of Table 1 is evaluated at zero, low, average, high, and very high levels of the accident rate variable (respectively the minimum and 25th, 50th, 75th, and 90th percentiles of the distribution). This coefficient, the average within-plant effect, is the smallest in magnitude. The zero accident rate months correspond to the zero level of production on the vertical axis in Figure 1. The production loss associated with a movement from zero accidents to the median accident rate is 1.31%, while a movement from zero accidents to the very high accident rate corresponds to a 2.94% drop in production.

These significant coefficients may seem small when recalibrated in terms of percentage shifts in production. However, with the available data, a 1% shift in production can be recalibrated in terms of changes in sales and then profits for each mill. For an average month in 1980 (a year in which paper prices were relatively low), a 1% increase in production (without any cost increases) is associated with a revenue increase of \$32,300 to \$169,400 depending on the mill. These 1% sales increases would have significantly affected the profits of these eleven mills. Nine of these mills had positive operating incomes during 1980; the other two did not turn a profit. For the nine with positive incomes in 1980, the monthly revenue increase associated with a 1% production increase translates into a 10.9% increase in operating income on average. For the two with negative operating incomes, the revenue increase from a 1% production gain would have reduced their average monthly loss by 17.1%. For those mills with positive operating incomes, a shift from the zero to the

Figure 1

ACCIDENT RATES AND CHANGES IN PRODUCTION



very high level of accidents (ignoring potential cost increases) would on average increase profits by one-third.

Omitted Variable Bias

Before presenting the different theoretical frameworks that can be used to interpret the observed accident rate-productivity relationship, I will first consider whether the estimated coefficients on the accident rate variable are spurious correlations that should be attributed to some other factor not included in the econometric models. Rather than estimate the magnitudes of possible errors under different assumptions about such a bias, I address this potential problem in a more direct way. Possible omitted variables that may be correlated with both accidents and production are taken from the literature on industrial safety⁶ and from interviews with mill managers and personnel. Data on these candidates were then collected from the mills and entered into the equation.

Most of the variables related to industrial safety suggested in the literature are already controlled for either by the structure of the sample or by variables already in the analysis. The production function already includes variables for manhours and number of paper machines so that scale controls have already been incorporated. Technology and the pace of work are controlled for by the homogeneity of the sample and the capital variables in the analysis. Furthermore, with workforces that are relatively homogeneous in terms of education and racial composition, the sample controls for many worker characteristics.

Data on other variables were collected as possible omitted variables: accession rate; operation of new machinery; and operation of the mill after a plant shutdown. The literature on industrial safety suggests that workforce experience may be correlated with safety as well as productivity. While job tenure was not consistently available from plants, its converse, the accession rate, was. Two additional sets of variables were suggested in interviews with plant personnel. It was suggested that when new machinery is being installed, accidents may be more common and productivity may be relatively low given the stated level of inputs. Four major machines were introduced in these plants during the 1976-1982 period. One dummy variable is created for the six-month period prior to the capitalization date of these machines to see if the installation period tends to disrupt existing plant operations. A second variable for the six-month period after the capitalization date is also created to see if the initial period of operation is one of high accident rates and low rates of productivity.

Finally, it was suggested in interviews that the period after a strike may also be a high accident rate-low productivity period. Months with strikes are not included in the sample on which the Table 1 results are based. During strikes, particularly several extended periods of strike activity during the 1976-1977 period, mills were either shut-down for lengthy periods or partially operated by managerial employees. The start-up after a mill has been idle or run by less experienced employees may then be a low productivity-high accident period. To test this hypothesis, a dummy variable was created for the first

quarter of operations after a strike.

To see if any of the variation in the accident rate variable is accounted for by these variables, the equations in Table 2 are estimated. Whether the plant dummies are included or not, the accession rate moves most closely with accident rates. As expected, accidents are more common in months when the accession rate is higher.

To see if these additional variables help explain any of the relationship between accidents and production shown in Table 1, the potential omitted variables are included along with the accident rate in the basic equation 1 model. The results from these equations are presented in Table 3. The coefficients on the accident rate variable remain similar in magnitude and level of significance to those presented in Table 1 even after these additional variables are included in the analysis. Among the newly added variables, the periods around the installation of new machinery appear to be the most important determinants of the level of production. Both before and after the capitalization dates of new machines, production is significantly lower than one would have expected given the stated level of inputs.

We now turn to the development of several different theoretical frameworks for interpreting this robust empirical relationship: in the face of a detailed set of controls for inputs, plant-specific factors, time-specific factors and several potential omitted variables, the partial correlation between accident rates and production is significant and negative. In particular, the discussion to follow will consider the degree to which the robust empirical relationship

Table 2: Correlates of Accident Rates^a

[Dependent Variable: OSAA accident rate; N=508]

	(1)	(2)
1. accession rate	.184** (.095)	.161** (.098)
2. pre-capitalization period	.016 (.013)	.016 (.012)
3. post-capitalization period	.019* (.013)	.016 (.014)
4. post strike period	.008 (.010)	.008 (.010)
5. plant dummies	no	yes
R ²	.016	.074

a - standard errors in parentheses

*** - significant at the .01-level, one-tailed test

** - significant at the .05-level, one-tailed test

* - significant at the .10-level, one-tailed test

Table 3: Accident Rates and Correlates of Accident Rates
in the Model of Paper Production^a
[Dependent Variable: ln Tons of Paper; N=508]

	(1)	(2)	(3)	(4)
1. accident rate	-.240** (.112)	-.206*** (.109)	-.261*** (.104)	-.214** (.103)
2. accession rate	-.025 (.237)	.055 (.229)	-.188 (.226)	-.126 (.221)
3. pre-capitaliza- tion period	-.230*** (.037)	-.112*** (.035)	-.198*** (.037)	-.073** (.034)
4. post-capitaliza- tion period	-.053* (.039)	-.076** (.039)	-.070** (.037)	-.072** (.038)
5. post-strike period	.030* (.024)	.038** (.023)	.010 (.023)	.009 (.023)
6. capital dummies	yes	no	yes	no
7. plant dummies	no	yes	no	yes
8. time dummies	no	no	yes	yes
9. other capital value, energy, and hourly manhours controls appearing in Equation 1.	yes	yes	yes	yes
R ²	.957	.960	.965	.967

a - standard errors in parentheses

*** - significant at the .01-level, one-tailed test

** - significant at the .05-level, one-tailed test

* - significant at the .10-level, one-tailed test

should be considered as evidence of constant efficiency or persistent inefficiency in microeconomic production.

IV. THEORETICAL FRAMEWORKS: INTERPRETING THE SAFETY - PRODUCTIVITY RELATIONSHIP

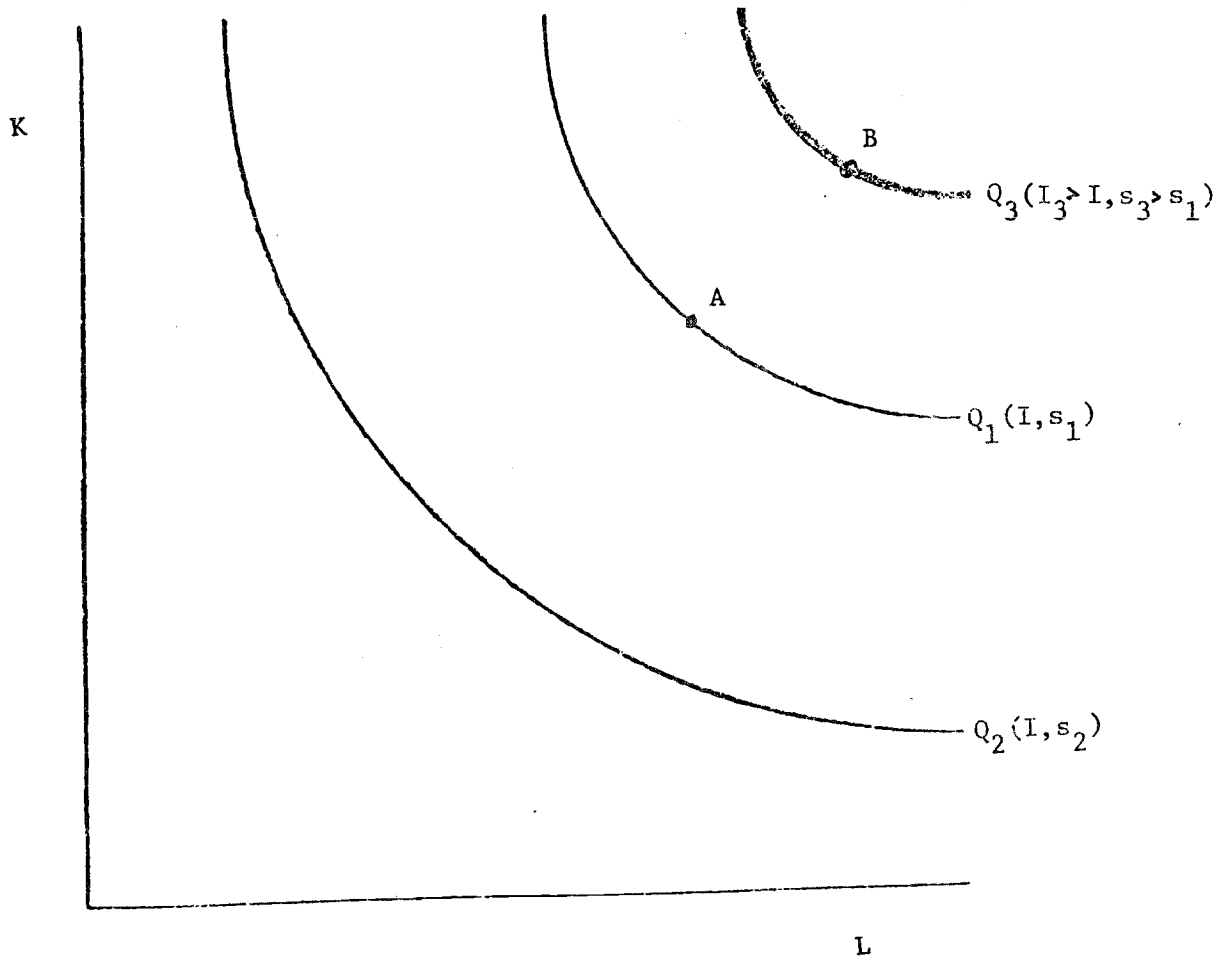
Theoretical Framework 1: The Conventional Economic View of Accidents as a Joint Product

The traditional view in economic theory for considering the relationship between production and safety considers the two factors as joint products. In his extensive review of the literature and findings concerning industrial safety, Oi provides this brief summary of the economic view:

Textbook production functions describe how inputs of labor and capital can be transformed into outputs of economic goods. A more accurate picture is one in which firms face joint production functions wherein inputs generate two joint products, economic goods X and work injuries or accidents A. If instead of injuries A we measure their complement, uninjured workers B, then for a given outlay for inputs, there is a negative technical trade-off between goods X and uninjured workers B. Given its outlays for labor, capital, and other inputs (including safety), a firm can expand its "output" of uninjured workers B (achieving a lower injury rate) only by reducing output of its principal product X.⁷

In this model, there is a positive relationship between accidents and output, ceteris paribus. While safety expenditures reduce accidents, the allocation of resources away from capital and labor inputs will decrease output. This model is shown in Figure 2. For purposes of exposition, let capital (K) and labor (L) represent all productive inputs. With total input endowment, I, and s_1 of that endowment devoted to safety, $Q(I, s_1)$ is realized. Under this standard formulation, if s_1 is increased to s_2 by

Figure 2



allocating resources away from K and L, output decreases from $Q_1 (I, s_1)$ to $Q_2 (I, s_2)$. Any movements between frontiers for which total input endowment is fixed would yield a positive (negative) relationship between accidents (safety) and output.

In order to reconcile this theory with the basic inverse relationship between accidents and output, one must believe that the empirical work does not control for differences in input endowment. For example, in Figure 2, output could be increased from Q_1 to Q_3 if the total input endowment is increased. Such an increase in output could also be associated with fewer accidents if enough of the additional input endowment is devoted to safety. The movement between points A and B in Figure 2 would reveal an inverse relationship between accidents and output.

The detailed set of input control variables makes this interpretation of the empirical result highly suspect. The basic production model controls for the total endowment of principal capital, labor, and energy inputs more completely than perhaps any existing study. More elaborate theoretical frameworks should therefore be considered.

First Elaboration: Accidents Reduce Efficiency of Inputs

In the previous frameworks, safety expenditures are not considered as an input that contributes to the production process. Specifically, consider accidents as disruptions that reduce the efficiency or utilization of other inputs. In Figure 2 then, the movement from point A to point B could be accomplished by holding fixed the level of capital and labor inputs and increasing the level of

safety expenditures. Output would expand as productivity-inhibiting accidents are reduced. If the empirical equations control for variations in the levels of most inputs, but not for variations in safety expenditures, the coefficients on the accident rate variable could still be mapping movements between well-defined frontiers.

This first elaboration, while a useful first step, still does not provide an entirely satisfactory framework that incorporates all of the empirical results from the last section. First, when the basic model is expanded to include plant dummies, the accident-production relationship is still significantly negative, and my interviews and site visits provided no evidence of any major changes in safety expenditures over time within mills. Second, and even more challenging to the view that the accident rate coefficients only map changes in output associated with changes in safety expenditures, the inverse relationship between accident rates and output remains significant even after the basic model is expanded to include plant dummies, month dummies, year dummies and a set of controls for potential omitted variables.

Second Elaboration: Accidents Have a Random Component

A given level of safety expenditures do not seem to guarantee a fixed accident rate. There is a great deal of variation in accident rates from month to month within each plant. Safety expenditures do not seem to vary to this extent, so that movements in the accident rate do not mirror changes in safety expenditures precisely. Therefore, accidents, A , can be considered to have a probabilistic component. Regardless of the level of safety expenditures, the accident rate is still a random variable governed by some probability distribu-

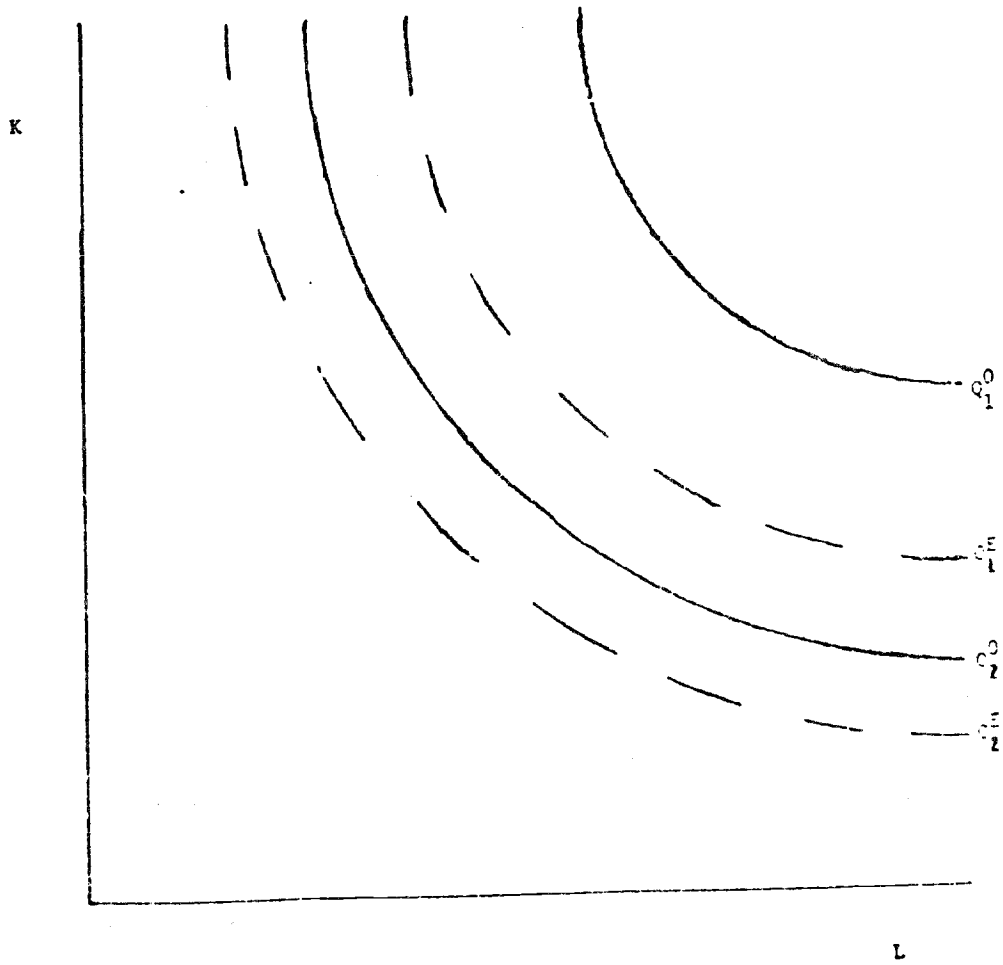
tion. With a fixed input endowment, I , and s_1 of I devoted to safety there is still a certain probability that a plant will have no accidents. For given levels of the parameters I and s , the no accident state is the most productive. However, the zero-accident production frontier, $Q_{\max}(I, s)$, is not guaranteed, since accidents are governed by a probability distribution. Expected output will be further influenced by the product of the probability of accidents and the effect of accidents on output. These elaborations can be summarized in the following equation:

$$E(Q) = Q_{\max}(I, s) + P_A(s) \cdot \frac{\partial Q}{\partial A} \quad (\text{Equation 2})$$

From this equation, one sees that safety expenditures determine expected output in two ways. First, when a larger share of the total input endowment is devoted to safety, the zero-accident frontier is closer to the origin of isoquant space. Second, safety expenditures also will reduce the probability of accidents. As in the first elaboration, accidents reduce the efficiency of other inputs, so that $\frac{\partial Q}{\partial A}$ is negative. Therefore, the two effects of safety expenditures on output are in opposite directions.

The Equation 2 model is shown in Figure 3. Q_1^0 is the maximum output possible with fixed input endowment I and s_1 devoted to safety. All points to the left of this zero-accident frontier are possible. Even zero output may occur in the rare event of an accident that halts production completely for an extended period. Safety expenditures influence the accident frequency distribution, and it is this distribution

Figure 3



that governs how often output is forced below Q_1° . Therefore, safety expenditures determine how far the expected output frontier Q_1^E lies below the maximum output frontier Q_1° .

Now, if safety expenditures are increased from s_1 to s_2 by reallocating resources away from capital and labor, the effects on output are more complicated than in the previous framework. The zero-accident frontier given s_2 , Q_2° , will lie below Q_1° . However, with $s_2 > s_1$, the expected accident rate is less under s_2 than it is under s_1 . The entire set of points to the left of Q_2° are still possible, but perturbations off the zero-accident frontier will not occur as frequently. In Figure 3, therefore, the width between Q_2^E and Q_2° is narrower than the width between Q_1^E and Q_1° . While the Q_2 -band lies entirely below the Q_1 -band in Figure 3, it is possible that the bands overlap. In fact, Q_2^E may exceed Q_1^E , so that expected output can be increased when a greater proportion of the total input endowment is devoted to safety.

With each elaboration to the theoretical framework, one is also introducing a more complicated, and probably more realistic, view of the role of managers. Under the initial framework with a fixed input endowment (in the absence of regulation), a manager selects safety expenditures equal to zero and maximizes output. With the first two elaborations, the decisions for the manager are more complex. Now a manager must weigh the loss in output from moving resources out of production against the gains associated with operating a safer, and therefore more productive, plant. To gauge these gains, a manager

must understand the effect of accidents on output, and the effects of safety expenditures on accidents.

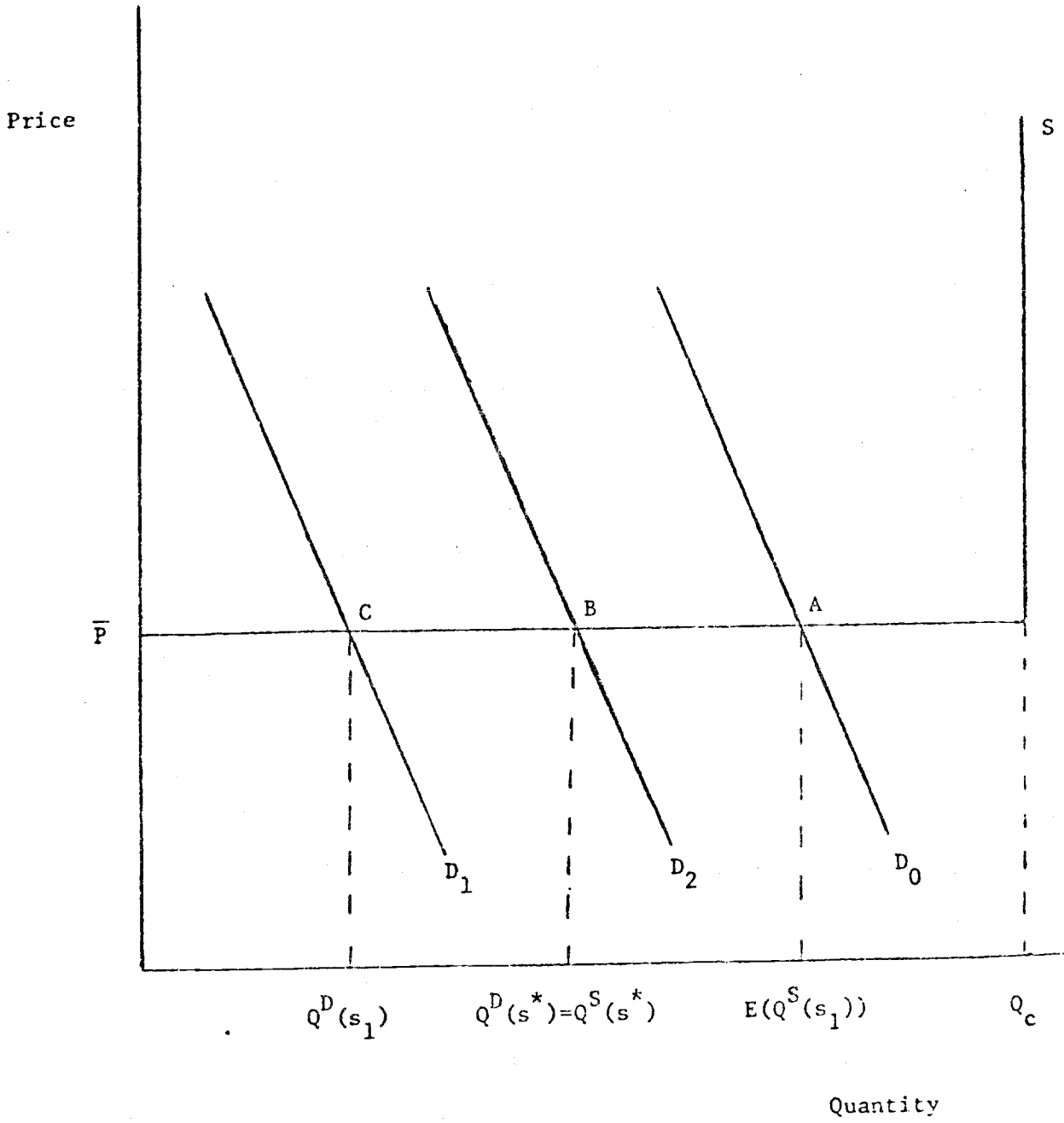
Third Elaboration: Random Disturbances to Production Discourage Customers

The theoretical elaborations introduced thus far show that a manager must search for that value of s that will maximize expected output. A third elaboration, also with accidents as a random disturbance to production, demonstrates that the manager's task may be even more complicated than just picking the outermost expected production frontier. Assume that the marginal cost of production is constant for each producer; therefore the firm's supply curve is horizontal where price equals marginal cost. However each firm faces a capacity constraint determined by the size of the plant. The supply curve becomes vertical at that value of capacity production, Q_C (see Figure 4). Because the firm's customers value certainty of deliveries (and therefore dependability of production), accidents may further affect the firm's revenue in any given period. The firm's customers make up his current demand, D_0 in Figure 4. The first equilibrium point (A) corresponds to the amount the firm expects to supply, $E(Q^S(s))$. This is the amount that was given by Equation 2

$$[Q^S = Q_{\max}(I, s) + P_A(s) \frac{\partial Q}{\partial A}].$$

However if the production manager does not recognize the effect that accidents have on quantity demanded, he will find that the expected quantity supplied $E(Q^S(s_1))$ may be greater than the quantity demanded, $Q^D(s_1)$, at his chosen level of safety expenditures. More specifically, once an "unexpected" level of accidents results in lower than expected production, previous customers will become unsatisfied. Risk averse customers, uncertain about future deliveries, will go to other producers. Although the

Figure 4



firm may produce at or above its expected output frontier in the following period, the demand he once faced is no longer there.

A more formal treatment of the hypothesis rests on the assumption that the quantity demanded, like that supplied, depends on the random disturbances, \tilde{A} :

$$Q^D = Q^D(P, \tilde{A}(s)) \quad (\text{Equation 3})$$

In the short run, the firm will want to generate the maximum revenue from its fixed endowment, I . The revenue function being maximized is given by:

$$\max_s (\text{Rev}) = \max_s P_Q \cdot Q \quad ; \quad (\text{Equation 4})$$

where

$$Q = \min(Q^S, Q^D) \quad ;$$

$$Q^D = Q^D(\bar{P}, \tilde{A}(s)) \quad ; \quad \text{and}$$

$$Q^S = Q_{\max}^S(I, s) + P_A(s) \frac{\partial Q}{\partial A} \quad .$$

Figure 4 shows that the expenditure on safety which maximizes expected output, s_1 , may not be the expenditure which maximizes revenue. Because s_1 eventually leads to a quantity demanded, $Q^D(s_1)$ which is lower than $Q^S(s_1)$, only $Q^D(s_1)$ is sold (point C in Figure 4); leftover output cannot be sold and revenue equals $P \cdot Q^D(s_1)$. The optimal s , s^* , may involve greater safety expenditures and a lower expected output. But the increase in sustained demand will generate increased revenue. With the random disturbances to production also influencing the level of sustained demand,

managers may no longer simply try to maximize expected output. Additional expenditures on safety will lead not only to a loss in expected output but a decrease in the variance of production. This more stable production can lead to an increase in sustained demand and therefore greater revenue in the long run.

This elaboration complicates the managerial decision process even further. The manager must now consider three effects of safety expenditures: (1) safety expenditures reduce output by diverting resources away from capital and labor; (2) they increase output by making productivity-inhibiting accidents less frequent; and (3) they increase profitability by reducing the variability of production, thereby stabilizing the demand from customers.

One might argue that an inventory would reduce the importance of considerations (2) and (3), particularly for a non-perishable product like paper. However, in the paper industry, final product inventories are of limited value. It is relatively easy to accommodate the detailed specifications of a customer's order for paper. The plant maintains large stocks of chemical dyes, coats, and bonding chemicals. Cutting and sheeting operations are also easily adapted to the detailed customer specifications. The final product will meet one customer's specifications, but few future orders will have those exact specifications. Inventories, in the particular case of the paper industry, are of limited value.

Fourth Elaboration: Accidents are Sources of Information

Once one realizes that accidents have a random component, and that safety expenditures can not guarantee a fixed level of accidents, it be-

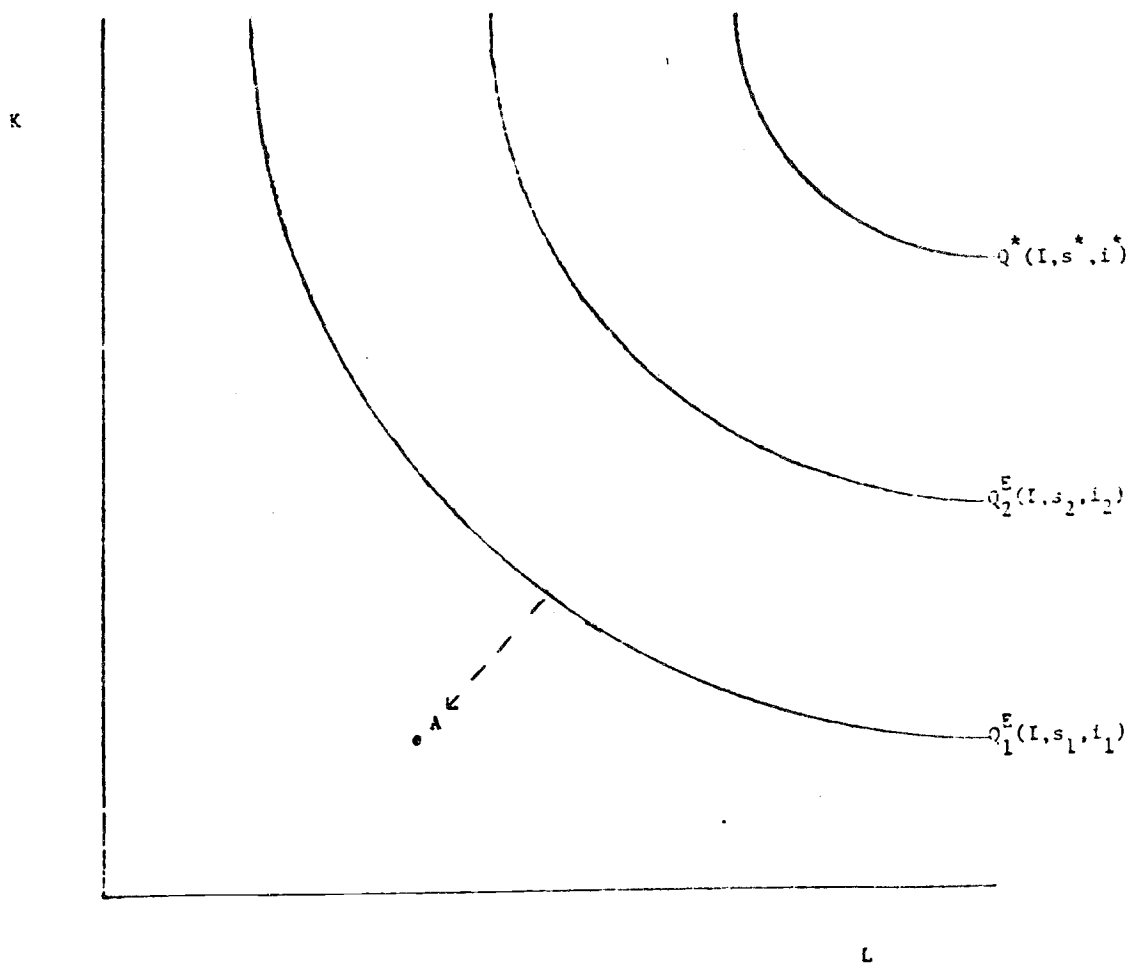
comes clear that managers must make a complicated set of decisions. A fourth elaboration leads one even further from the simplest economic framework and provides an even more accurate representation of the firm. Consider a brand new plant with "frontier" technology. The manager has considered the three effects of safety expenditures and has made optimal safety expenditures in several areas (maintenance, inspections, safety gear and equipment, employee seminars, etc.).

As in the previous model, these safety expenditures, s_1 , define an expected output frontier, Q_1^E . However, accidents will occasionally force production inside its expected frontier. Now, elaborate on the model so that accidents are not only random disturbances but also sources of information. Viewed in this way, accidents reveal trouble spots. After an accident, a manager estimates that the probability of another accident in the same spot is quite high and makes the necessary investments to fix the trouble spot. While the increase in safety expenditures from s_1 to s_2 takes resources away from capital and labor, the shift in the expected isoquant is not toward the origin but away from it. This is because the manager's stock of information about his plant has increased from i_1 to i_2 . The more efficient safety expenditure s_2 was not made in state 1 since it would have been too costly to find the trouble spot. Put another way, in state 1 it would have been very costly (extensive policing of the plant) to locate the trouble spot. Now with greater information in state 2, a small expenditure repairs the trouble spot.

Figure 5 depicts this model. The Q_1^E contour shows production with total input endowment, I , safety expenditures, s_1 , the expected level of accidents, and stock of information, i_1 . An accident occurs forcing production to point A which is below the Q_1^E isoquant. After the accident, two changes in the parameters occur. The information stock increases to i_2 and safety expenditures are increased to s_2 . The net effect of the changes is to move the expected state 2 isoquant, Q_2^E , away from the origin.

The outermost frontier of production in Figure 5, Q^* , is never realized, since there will never be perfect information, i^* . One now might introduce another elaboration involving search activity to the basic economic framework. To maintain the production frontier construct, one could consider "search activity as one competitor for internal resources, and [that] expenditures for search are made up to the point where the marginal cost of search equals the marginal expected return from it."⁸ Regardless of any attempts to model or measure such an intangible input, one must also recognize that the four theoretical elaborations that have been developed to provide a more realistic framework for interpreting the empirical results in this study have altered the conventional production frontier construct considerably. It is perhaps more reasonable to believe that empirical micro-productivity research, as in this study, estimates some sort of "average" production function through some fuzzy band of observed input-output configurations. It would be difficult to describe this average production function

Figure 5



as a true "frontier," since observed production will often exceed the input-output points along the average production function. Across competitors over long periods of time, disturbances to production would have to be relatively equal for all firms to remain part of the industry. For data aggregated over time or firms, however, the production frontier framework might be a more reasonable approximation as disruptions to production average out. However, the deterministic production frontier framework can be a misleading description of the actual day-to-day operations of individual firms.

VI. CONCLUSION - HOW FAR INSIDE THE FRONTIER?

The magnitude of the disturbance effect of accidents on production ranges to about 3% of production. A 3% shift in production is shown to correspond to a sizeable shift in profits. The effect of accidents on the performance of firms was selected for this study since it seemed that accidents by their very nature should be thought of as having a random component. Expenditures on safety do not guarantee a fixed level of accidents. The accident rate coefficients, in equations with detailed sets of controls for variations in the level of productive inputs, could therefore represent disruptions to the production process. Still, the magnitude of these disruptions may be viewed as a second-order consideration. However, safety is only one dimension of plant operations. By considering just one additional factor that keeps firms inside their frontier, one begins to realize that the distance between observed production and frontier production may be substantial.

Strikes have long been recognized as economically inefficient phenomena.⁹ Both labor and management would have been better off had they reached the eventual solution without a strike. With the rare exception of times when managers partially operated plants during strikes, plants were at the origin of isoquant space when on strike--clearly on no frontier. In this sample, over the period from January 1976 to September 1982, strike days in the mills ranged from a low of no days to 239 days (or 9.7% of all potential operating days). On average, a mill lost 6.0% of potential operating days. Under the assumption that a mill would have matched its production in the same

month of the previous year had it not been on strike, one finds that mills lost up to 10.6% of total production over the period to strikes. The average loss was 6.4%. Moreover, with salaried personnel still on the payroll and expensive capital idle, the shutdowns during strikes in this industry provide staggering examples of microeconomic inefficiency.

By considering this one additional dimension, the distance between observed production and frontier production widens substantially. Furthermore, in other sectors, when production is not machine-paced and more under the control of employees, these disturbances may be even more noticeable. In short, the theoretical elaborations that suggest that firms operate inside and not on frontiers can be more than a second-order consideration--particularly for empirical research at the micro-level.

In addition, this theoretical distinction in the framework for analyzing microeconomic production generates very different research questions. The dimensions which are subject to managerial discretion and decision making must be better documented. These dimensions and their effects on productivity should be an active area of micro-level research. At aggregate levels of analysis, the deterministic frontier framework provides a useful theoretical construct. However, at the micro-level one should try to allow for interpretations that acknowledge the sources of microeconomic inefficiency.

The view of the firm developed through detailed empirical analyses of similar firms provides a significant set of elaborations to the basic economic framework of well defined production frontiers. Here, the real frontier is

viewed as some unreachable moving target. Managers must make decisions along a number of dimensions to run their firms. Each dimension involves a number of detailed component decisions. The safety dimension, for example, involves decisions about capital equipment, safety gear, awareness programs and responses to regulatory guidelines. Decisions are made in each area. After the resulting performance is evaluated, adjustments are made. Even in the most competitive of environments, firms will vary in their decisions, their investments, and therefore their performance. Furthermore, a poor managerial decision in one area which leads to some degree of microeconomic inefficiency can be counterbalanced by any number of sound managerial decisions not matched by competitors. What is required in a competitive environment is not a correct decision and investment at every turn. With the countless number of decisions required to run a firm, that is not possible. A firm does, however, have to make enough correct decisions so that its performance does not lag behind that of its competitors for too long. Firms that fair poorly today can remain viable competitors since dynamic adjustments can lead to more rapid movements toward that ever moving, unreachable final frontier of production. Detailed observation of the operations of similar firms and analysis of data on their production processes leads to much the same conclusion that Liebenstein developed over twenty years ago: "the production frontier is neither completely specified or known. An experimental factor always exists." 10

FOOTNOTES

1. Liebenstein, "Allocative Efficiency vs. X-Efficiency," American Economic Review, June 1966, Vol. 56.
2. Simon, Herbert A., Models of Man (New York: Wiley, 1957).
3. Cyert, Richard M., and James G. March, A Behavioral Theory of the Firm (Englewood Cliffs, N.J.: Prentice Hall, Inc., 1963).
4. Ichniowski, Casey, "Micro-Production Functions Aren't Pretty: Firm-Level and Industry-Level Specification for Inputs and Outputs," NBER Working Paper No. 1365, Cambridge, Massachusetts (June 1984).
5. Ibid. pp. 19-21.
6. For a useful summary, see Oi, Walter Y., "On the Economics of Industrial Safety," Law and Contemporary Problems, Summer/Autumn 1974, pp. 669-699.
7. Oi, "On the Economics of Industrial Safety," p. 674.
8. Cyert and March, p. 10.
9. Hicks, John R., The Theory of Wages (New York: Macmillan, 1932), Chapter 2.
10. Liebenstein, pp. 406-407.