R&D Depreciation, Stocks, User Costs and Productivity Growth for US Knowledge Intensive Industries

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Abstract

This paper estimates R&D depreciation rates for U.S. knowledge intensive industries. R&D depreciates at an annual rate of; 18 percent for chemical products, 26 percent for nonelectrical machinery, 29 percent for electrical products, and 21 percent for transportation equipment. These rates imply that R&D depreciates 2 to 7 times faster than physical capital stocks in these industries. Based on these depreciation rates, new estimates of R&D user costs imply that the marginal (gross of depreciation) returns to R&D capital are; 0.25 for chemical products, 0.31 for nonelectrical machinery, 0.34 for electrical products, and 0.27 for transportation equipment. R&D investment also significantly contributed to productivity gains. R&D contributed virtually 100 percent to productivity growth in chemical products, 55 percent in nonelectrical machinery, 38 percent in electrical products, and 84 percent in transportation equipment.

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1. INTRODUCTION

The growth of research and development (R&D) capital critically depends on its 'economically useful' life. For example, an acceleration in R&D depreciation causes relatively more resources to be devoted to knowledge creating activities in order to sustain a constant knowledge outcome. This resource re-allocation raises the opportunity cost of R&D, and thereby, with all other things constant, reduces the rate of knowledge creation. Thus, estimates of R&D depreciation rates are a critical component for the measurement of R&D capital. The first objective of this paper is to estimate R&D depreciation rates for the major U. S. knowledge intensive industries; namely chemical products (SIC 28), nonelectrical machinery (SIC 35), electrical products (SIC 36), and transportation equipment (SIC 37). These four industries account for 78 percent of manufacturing R&D expenditures, and 60 percent of business sector R&D.[1] The second objective is to compute the R&D capital stocks for these industries, based upon the estimated depreciation rates.

R&D is a durable or capital input, since its productive capability lasts for more than one period. Consequently, accounting for the productive contribution of R&D involves an evaluation of its benefits over several periods. Jorgenson and Griliches [1967], Diewert [1980], Hulten and Wykoff [1981], Harper, Berndt and Wood [1989], and Hulten [1990] recognize that an appropriate evaluation implies a distinction between the price of using or renting an asset over time, and the price of owning or purchasing it on a particular date. The two prices are related in the following manner; the price of ownership equals the discounted expected stream of future rental payments or user costs that the asset is expected to yield over time. With respect to the measurement of R&D capital, this price distinction creates complications for 'own use' situations, as the implicit asset 'transfer' between owner and user results in user costs that are not observed in market data. This unobservablity problem is particularly acute for R&D, since typically it is not market-transacted. The third objective of this paper is to calculate R&D user costs for the industries, and further using the new user costs, new estimates of R&D price elasticities are provided.

Research and development (R&D) accumulation is an important determinant of productivity growth (see the survey by Griliches [1995]). Investment in R&D reduces production cost, as inputs are more effectively transformed into outputs, and it alters output characteristics, thereby providing new products to the marketplace. These features of R&D enhance productive efficiency, and consequently improve productivity performance. Using the new estimates of R&D stocks and user costs, the last objective of this paper is to determine the contribution of R&D to total factor productivity growth for each of the R&D intensive industries.

This paper considers R&D depreciation within the context of intertemporal cost minimization, where depreciation rates are estimated simultaneously with other parameters characterizing the overall structure of production. Depreciation rates reflect technical efficiency and indicate the productiveness of 'old' capital required to generate the same level of services as 'new' capital (Jorgenson [1989], and Hulten and Wykoff [1996]). The approach here is consistent with the empirical work of Epstein and Denny [1980], Kollintzas and Choi [1985], Nadiri and Prucha [1996]. The model under consideration is an extension of Bernstein, Mamuneas and Pashardes [2004], where production decisions regarding nondurable, and capital input requirements involve intertemporal considerations. Moreover, since a proper evaluation of the productive contribution of R&D capital involves future prices, expectations are an important element of the evaluation process. In this paper price expectation generating processes are jointly estimated with the production structure.

The paper is organized in the following manner. Section 2 develops the theoretical model providing the framework to estimate R&D depreciation rates. Section 3 contains the discussion on the empirical specification, the regression results, the calculation of R&D capital stocks and user costs. Section 4 addresses the estimated own and cross price elasticities, including those associated with the computed R&D capital. Section 5 develops and decomposes total factor productivity growth rates, and determines the contribution of R&D capital. The last section concludes the paper.

2. PRODUCTION WITH DEPRECIATING R&D

This section develops a model of production inclusive of the parameterization of R&D depreciation. The framework extends Bernstein, Mamuneas Pashardes [2004], and forms the basis for the estimation model in the following section. To begin, consider a production function written as:

$$y_t = F(v_{1t-1} + h_1(v_{1t} - v_{1t-1}), ..., v_{nt-1} + h_n(v_{nt} - v_{nt-1}), t), \tag{1}$$

where y_t is output quantity in period t, F is the production function, v_{it} is the ith input quantity in period t, and t also represents the exogenous disembodied technology index.[2] In equation (1) the h_i $i = 1, ..., n$ parameters provide for changes in technical efficiency levels accompanying factor additions. These parameters reflect the variations in 'net' efficiency by capturing the net gains from factor improvements ($h_i > 1$), or the net losses associated with adjustment costs ($0 < h_i < 1$). Notice if $h_i = 1$, for $i = 1, ..., n$, the productive efficiency of an additional factor equals the current efficiency level for the input, and the standard production function, $y_t = F(v_{1t}, ..., v_{nt}, t)$, emerges.[3]

Factor accumulation is represented by

$$v_{it} = x_{it} + (1 - \delta_i)v_{it-1}, \; i = 1, ..., n, \tag{2}$$

where x_{it} is the addition to the ith input quantity in period t, and $0 \leq \delta_i \leq 1$ is the ith input depreciation rate. Since the depreciation rates for nondurable input quantities are defined as $\delta_i = 1$, in these cases from (2) $v_{it} = x_{it}$. The depreciation rate for physical capital is known, with $0 < \delta_i < 1$. The depreciation rate for R&D capital is unknown and to be estimated. Expression (2) characterizes R&D depreciation as a geometric or declining balance form. Griliches, in a series of papers [1979, 1990, and 1995], provides a justification for this depreciation profile based on two observations: i) There is approximately a contemporaneous link between R&D and the services emanating from this investment through innovation and invention, and ii) Typically innovation and invention are short-lived, and replaced at a rapid rate. Taken together these two results suggest efficiency declines relatively faster in the early part of the service life of R&D investment, and consequently R&D depreciation approximates declining balance.[4]

Input demands are determined from minimizing the expected present value of acquisition and hiring costs. The expected present value at time t (defined as the current time period) is given by the following:

$$\sum_{s=0}^{\infty}\sum_{i=1}^{n} a(t,t+s)q^{e}_{it+s}x_{it+s}, \tag{3}$$

where q^{e}_{it+s} is the expectation in the current period t of the ith factor acquisition (or hiring) price in period $t+s$, and $a(t,t+s)$ is the discount factor with $a(t,t)=1$, $a(t,t+1)=(1+\rho_{t+1})^{-1}$, where ρ_{t+1} is the discount rate from period t to period $t+1$.[5] The expression in (3) is minimized subject to equation sets (1), and (2).[6] The Lagrangian for the problem is:

$$\mathcal{L}=\sum_{s=0}^{\infty} a(t,t+s)\left\{\sum_{i=1}^{n} q^{e}_{it+s}\left[v_{it+s}-(1-\delta_i)\,v_{it+s-1}\right]\right.$$
$$\left. -\lambda_{t+s}\left[F\left(h_1(v_{1t+s}-\mu_1 v_{1t+s-1}),...,h_n(v_{nt+s}-\mu_n v_{nt+s-1}),t+s\right)-y_{t+s}\right]\right\} \tag{4}$$

where λ_{t+s} is the Lagrangian multiplier in period $t+s$, and $\mu_i=(1-h_i^{-1})$. Differentiating (4) with respect to v_{it+s}, and defining $z_{it+s}=h_i(v_{it+s}-\mu_i v_{it+s-1})$, the first order condition for the ith input in period $t+s$ is:

$$\lambda_{t+s}\frac{\partial F}{\partial z_{it+s}}h_i = w^{e}_{it+s}+a\mu_i\lambda_{t+s+1}\frac{\partial F}{\partial z_{it+s+1}}h_i,\ \ i=1,...,n, \tag{5}$$

where $w^{e}_{it+s}=q^{e}_{t+s}-aq^{e}_{it+s+1}(1-\delta_i)$, is the ith factor price in period t, but expected in period $t+s$, and $a=a(t,t+s+1)/a(t,t+s)$ is the constant discount factor.

Evaluating (5) for the time periods from t to $t+T$, solving the system recursively with $T=\infty$, and imposing the transversality condition that the shadow value of the marginal product for each factor is zero, that is $\lambda_{t+T+1}\partial F/\partial v_{it+T+1}=0$, for $i=1,...,n$, at $T=\infty$, then:

$$\lambda_t\frac{\partial F}{\partial z_{it}} = h_i^{-1}\left\{w_{it}+\sum_{s=1}^{\infty} w^{e}_{it+s}(a\mu_i)^{s}\right\},\ \ i=1,...,n, \tag{6}$$

where $w_{it}=q_t-aq^{e}_{it+1}(1-\delta_i)$. From the definition of $z_{it+s}=h_i(v_{it+s}-\mu_i v_{it+s-1})$, this variable represents efficiency-adjusted quantity. Therefore equation (6) shows the intuitive result that the value of the marginal product for each efficiency-adjusted input equals its respective user cost, which is defined by the right side of (6) (call ω_{it} the ith user cost in period t).[7]

The user cost derivation enables us to recast the problem defined by (3). in the following equivalent form:

$$\min_{z_{it}} \sum_{i=1}^{n} \omega_{it} z_{it}, \tag{7}$$

subject to the production function given by $y_t = F(z_{1t}, ..., z_{nt}, t)$, for periods $t = 0, ..., \infty$. The problem in (7) relates to minimizing efficiency-adjusted production costs, and leads to the first order conditions denoted by (6). The equivalency of cost minimizing problems enables us to define a cost function, which is denoted as:

$$C(\omega_{1t}, ..., \omega_{nt}, y_t, t). \tag{8}$$

This function depends on user costs, (and thereby depreciation and technical efficiency parameters, expected acquisition and hiring prices), output quantity, and technology indicator.

By differentiating (8) with respect to the user costs, it is possible to retrieve the efficiency-adjusted factor demands according to:

$$Z_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = \frac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}}, \ i = 1, ..., n. \tag{9}$$

Equation set (9) cannot be estimated due to the unobservability of efficiency-adjusted factor demands. These variables are unobservable because the technical efficiency parameters are unknown, and in addition for R&D capital, the depreciation rate is unknown. However, from equation (2) $v_{it} = x_{it} + (1 - \delta_i)v_{it-1}$, then (the observable) x_{it} can be substituted into (9), using $Z_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = h_i(v_{it} - \mu_i v_{it-1})$, to provide:

$$X_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = h_i^{-1} \frac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}} + (\mu_i - 1 + \delta_i)v_{it-1}, \ i = 1, ..., n. \tag{10}$$

Further rewriting (2) as $v_{it-1} = \sum_{\tau=0}^{T}(1 - \delta_i)^{\tau} x_{it-1-\tau}$, enables us to substitute for v_{it-1} in equation (10), which then becomes:

$$X_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = h_i^{-1} \frac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}} + (\mu_i - d_i) \sum_{\tau=0}^{T} d_i^{\tau} x_{it-1-\tau}, \ i = 1, ..., n. \tag{11}$$

where $d_i = 1 - \delta_i$. For nondurable inputs such as labor and intermediate inputs $\delta_i = 1$, and so (11) simplifies to $X_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = h_i^{-1} \frac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}} + \mu_i x_{it-1}$. Equation set (11) shows the equilibrium conditions in terms of observable quantities, and forms the basis for the estimation model, which is specified in the following section.

3. R&D DEPRECIATION RATES, STOCKS AND USER COSTS

This section specifies the cost function, and the price expectation generating processes for the acquisition and hiring prices required to estimate the model. The estimation results are presented, and then R&D capital stocks and user costs are calculated for the U.S. R&D intensive industries.

The cost function, is assumed to be the symmetric generalized McFadden functional form:

$$c_t = \left(\sum_{i=1}^{n} \beta_i \omega_{it} + \frac{.5 \sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} \omega_{it} \omega_{jt}}{\sum_{i=1}^{n} b_i \omega_{it}} + \sum_{i=1}^{n} \beta_{it} \omega_{it} t + \beta_{tt} t^2 \sum_{i=1}^{n} b_i \omega_{it} \right) y_t + \sum_{i=1}^{n} \alpha_i \omega_{it} + \alpha_t t \sum_{i=1}^{n} b_i \omega_{it} + \alpha_{yy} y_t^2 \sum_{i=1}^{n} b_i \omega_{it}, \tag{12}$$

where the parameters are denoted by the α's and β's. The $n \times n$ matrix formed by the β_{ij}, parameters is symmetric, and must be negative semidefinite so that the function is concave in user costs. The b_i, $i = 1, ..., n$ are nonnegative constants that are not all zero for some reference time period τ. For the reference time period, the cost function is homogenous of degree one in user costs if $\sum_{i=1}^{n} \beta_{ij} \omega_{i\tau} = 0$, and $\sum_{i=1}^{n} b_i \omega_{i\tau} \neq 0$. The expression $\sum_{i=1}^{n} b_i \omega_{it}$ is an index of input prices, and the constants b_i, $i = 1, ..., n$, are set equal to the input cost shares in the reference time period.[8] This functional form is attractive because it is a flexible functional form (Diewert and Wales [1988]) that retains flexibility under the imposition of concavity with respect to user costs.

Based on the specified cost function, (12), and dividing (11) by output quantity, ith investment demand per unit of output, or the ith investment intensity, becomes:

$$\frac{X_i(\omega_{1t},...,\omega_{nt},y_t,t)}{y_t} = h_i^{-1}\left\{\beta_i + \frac{\sum_{j=1}^n \beta_{ij}\omega_{jt}}{\sum_{i=1}^n b_i\omega_{it}} - \frac{.5b_i\sum_{i=1}^n\sum_{j=1}^n \beta_{ij}\omega_{it}\omega_{jt}}{(\sum_{i=1}^n b_i\omega_{it})^2}\right.$$
$$\left. + \beta_{it}t + \beta_{tt}b_i t^2 + \frac{\alpha_i}{y_t} + \frac{b_i\alpha_t t}{y_t} + b_i\alpha_{yy}y_t\right\} + (\mu_i - d_i)\sum_{\tau=0}^{T} d_i^{\tau}\frac{x_{it-1-\tau}}{y_t}, i = 1,...,n. \quad (13)$$

Notice that (13), which forms part of the estimation model, did not contain an output efficiency parameter. If this parameter, γ, is introduced, then the production function becomes $\gamma y_t = F(z_t, t)$, where z_t is the vector of efficiency-adjusted inputs. However, this parameter is not identifiable. To see this, suppose for simplicity technological change is neutral and constant, then $\gamma y_t = F(z_t, t) = \beta F(z_t)$, and thus $y_t = \eta F(z_t)$, where $\eta = \beta/\gamma$, and so γ is not identified. Thus without loss of generality γ can be set to unity, and therefore the production function , F, actually embodies output efficiency.[9]

A further point on parameter identification arises with respect to efficiency (h_i or μ_i) and depreciation rate (δ_i) parameters. From expression (13), since $\mu_i = 1 - h_i^{-1}$, and $d_i = (1 - \delta_i)$, a proportional increase in all efficiency and depreciation rate parameters at period t leaves the expression unaffected. Thus the depreciation and efficiency parameters are not separately identified. Since economic depreciation represents a metric to evaluate a durable input on a constant efficiency basis (see Jorgenson [1989], and Hulten [1990]) then, intuitively, it is redundant to define both efficiency and depreciation parameters. Thus for R&D capital the efficiency parameter is normalized to unity. This problem does not arise for the other factors of production, since depreciation is a measured rate for physical capital, and set to unity for the non-capital inputs.

The next requirement for estimation, which involves the expectation generating processes for acquisition and hiring prices. It is assumed that price expectations follow a first order autoregressive process:[10]

$$q_{it+1} = \phi_i + \theta_i q_{it} + e_{it},\ i = 1,...,n, \quad (14)$$

where ϕ_i, and θ_i are parameters, e_{it} is identically and independently distributed over time, and since expectations are rational, the expected value of e_{it} is zero. Equation set (14) implies in the current period t, that the ith expected acquisition or hiring price in period $t+s$ is,

$$q_{it+s}^{e} = \frac{\phi_i(1-\theta_i^s)}{(1-\theta_i)} + \theta_i^s q_{it},\ i = 1, ..., n. \tag{15}$$

Equation set (15) shows the price expectations terms to be used in the user cost formulas. Substituting (15) into the right side of (6), expanding the geometric progression, and collecting terms, the user costs become:

$$\omega_{it} = h_i^{-1}\left[q_{it}\frac{1-ad_i\theta_i}{1-a\mu_i\theta_i} + \frac{\phi_i}{1-\theta_i}\left(\frac{1-ad_i}{1-a\mu_i} - \frac{1-ad_i\theta_i}{1-a\mu_i\theta_i}\right)\right],\ i = 1, ..., n, \tag{16}$$

Specifying the price expectations processes reveals that the user costs are unobservable because of the technical efficiency parameters, $h_i = 1/(1-\mu_i)$, the expectations parameters (ϕ_i, θ_i), and in the case of R&D capital the depreciation rate $\delta_i = (1-d_i)$.

With the cost function and price expectations processes specified, the estimation model becomes (13) (with (16) defining the user costs), and (14). The errors, $u_t = (u_{1t}, ..., u_{nt})$, relating to equation set (13) are assumed to be identically, and independently distributed over time with zero expected value.[11] In addition, with the errors from (14), which are $e_t = (e_{1t}, ..., e_{nt})$, let $E\left[(u_t, e_t)(u_s, e_s)^T\right] = \Theta$, for all s, t if $s = t$, and 0 if $s \neq t$, where Θ is the positive definite covariance matrix. Equation sets (13) and (14) are jointly estimated by the Nonlinear Seemingly Unrelated Regression estimator, applied to data over the period from 1954 to 2000. There are four factors of production, labor, intermediate inputs, physical capital, and R&D capital, and thus expressions (13) and (14) consist of eight equations, four investment intensity equations, and four equations relating to price expectations. The model is estimated for four industries; chemical products, nonelectrical machinery, electrical products, and transportation equipment. The data for each of the industries are discussed and presented in the Appendix.

A number of versions of the model were estimated in order to conduct tests on the efficiency and expectations parameters. First, the model was estimated to determine whether technical efficiency between new and current inputs differ. Thus there were two versions; $h_i \neq 1$, or $\mu_i \neq 0$, and $h_i = 1$, or $\mu_i = 0$.[12] Second, each of the two versions were estimated with *AR(1)* and constant (or static) price expectations processes. The estimates for $h_i \neq 1$

and *AR(1)* price expectations are presented in table 1.[13] Table 2 presents the results from a number of hypotheses tests. The first row shows that the hypothesis of no difference in technical efficiency, $h_i = 1$, is rejected for each of the factors of production.[14] The second row shows that constant price expectations can also be rejected, as the price expectation parameters differ from one. Since the models with *AR(1)* and constant price expectations processes are not nested, there is also a joint test for no efficiency change and constant price expectations. This specification is also rejected, as shown in the third row of table 2.[15] To summarize, the results indicate that new factors are relatively more efficient than current inputs, and efficiency levels differ among the new factors of production, while price expectations are not static, but follow an *AR(1)* process.

In table 2 the results of a number of tests on the residuals are provided. Tests are conducted for non-spherical disturbances. First order, and combined first and second order serial correlation are rejected and ARCH is also rejected.[16] Table 2 also provides the results of a test relating to concavity of the cost function with respect to the user costs. Concavity imposed using the Wiley, Schmidt and Bramble [1973] technique, cannot be rejected for chemical products, nonelectrical machinery, and electrical products. Concavity was satisfied for transportation equipment.

>From the regression results of the preferred model presented in table 1, estimates of the R&D depreciation rate, δ_r are; 18 percent for chemical products, 26 percent for nonelectrical machinery, 29 percent for electrical products, and 21 percent for transportation equipment. These rates imply that R&D capital depreciates in about three to five years. Moreover, since the depreciation rates for physical capital range from 4 percent to 8 percent, then R&D capital depreciates at 2 to 7 times the rate of physical capital. There are few studies estimating R&D depreciation rates. Nadiri and Prucha [1996] estimate a rate of 12 percent for the manufacturing sector; Baruch and Sougiannis (1999) estimate rates of 5-16 percent for chemicals and pharmaceuticals, 8-19 percent for machinery and computers, 4-20 percent for electrical and electronics, 7-17 percent for transportation, 13-24 percent for scientific instruments, and overall industries 11-20 percent; while Ballester, Garcia-Ayuso, and Livnat (2004) estimate a rate of 12 percent for chemical and pharmaceuticals, 17 percent for

machinery and computers, 18 percent for electrical and electronics, 20 percent for transportation, and 15 percent for scientific instruments. A common result among all studies finds R&D depreciating more rapidly than physical capital.

The estimates of the efficiency parameters suggest that technical efficiency levels increase with factors additions. Moreover, since $h_i = 1$ implies that efficiency does not change, then the rate of efficiency growth for the ith input can be defined as $h_i - 1$. From the estimates of the h_i^{-1} parameters in table 1; efficiency growth in chemical products is 4.00 percent for labor, 1.29 percent for physical capital, and 2.98 percent for intermediate inputs, for nonelectrical machinery the growth rates are 0.53 percent for labor, 3.74 for physical capital, and 0.49 percent for intermediate inputs, for electrical products efficiency growth is 0.62 percent for labor, 1.63 percent for physical capital, 0.62 percent for intermediate inputs,and efficiency growth in transportation equipment is 1.22 percent for labor, 2.44 percent for physical capital, 0.29 percent for intermediate inputs. These results suggest that efficiency growth for physical capital generally exceeds the other factors of production, while efficiency growth for labor and intermediate inputs are relatively similar.

The R&D capital stocks and user costs for the four industries are presented in table 3, and figures 1-4, which also contain, as a reference, stocks and user costs under the assumption of 10 percent depreciation. The R&D stocks are constructed by application of equation (2), or equivalently $v_{it} = \sum_{\tau=0}^{T}(1-\delta_i)^{\tau} x_{it-\tau}$, where v_{it} is the R&D stock in period t, $x_{it-\tau}$ is R&D investment in period $t-\tau$, and δ_i is the R&D depreciation rate. From table 3, over the period from 1955 to 1999 the R&D stocks grew by; 143.42 percent in chemical products, 106.58 percent in nonelectrical machinery, 86.64 percent in electrical products, and 8.44 percent in transportation equipment. From figure 4, the relatively low growth rate for transportation equipment reflects the rather cyclical nature of R&D activity in the industry. From table 3, R&D capital growth in chemicals and nonelectrical machinery outpaced the growth in electrical products, which in turn exceeded R&D growth in transportation. The average annual growth rates in the four industries were respectively; 3.26 percent, 2.42 percent, 1.97 percent, and 0.19 percent.

Table 3 and figures 1 to 4 also present R&D user costs. These user costs are novel for two reasons. First, they include the estimated rates of depreciation, and second they embody estimated price expectations parameters. This approach differs from the typical procedure used to construct R&D user costs, where 'a priori' assumptions are invoked for depreciation rates and future price changes. In 1996, the reference time period, the user costs are; 0.246 for chemical products, 0.313 for nonelectrical machinery, 0.342 for electrical products, and 0.273 for transportation equipment. Since the computed user costs represent the (gross of depreciation) marginal return to R&D capital, then marginal returns to R&D in nonelectrical machinery and electrical products are equal, and exceed the marginal returns in chemical products and transportation equipment.

4. PRICE ELASTICITIES

With the new calculations of R&D capital stocks and user costs, it is possible to provide new price elasticity estimates associated with R&D. This section presents the set of all factor price elasticities, including the own and cross price elasticities relating to R&D capital. Price elasticities are of interest in their own right, but in addition, since specific tax incentives have been implemented to encourage R&D activities (see Hall and van Reenen [2000]), a proper evaluation of these incentives requires price elasticity estimates.

The elasticity of demand for input i, with respect to the user cost of input j, ω_{jt}, is defined as:

$$\epsilon_{ijt} = \left[\partial V_i \binom{\cdot}{t} ./\partial \omega_{jt}\right] (\omega_{jt}/v^*_{it}) \quad , \quad i = 1, 2, ..., n, \tag{17}$$

where from (2) and (10) $v^*_{it} = V_i \binom{\cdot}{t} = h_i^{-1} \dfrac{\partial C(\omega_{1t}, ..., \omega_{nt}, y_t, t)}{\partial \omega_{it}} + \mu_i v_{it-1}$ is the demand function for input i. Moreover, using equation (9), and defining the right side of (9) as z^*_{it}, the price elasticities of demand can be rewritten as;

$$\epsilon_{ijt} = h_i^{-1} \left[\partial Z_i \binom{\cdot}{t} ./\partial \omega_{jt}\right] \left[\omega_{jt}/ \left(h_i^{-1} z^*_{it} + \mu_i v_{it-1}\right)\right] \quad , \quad i = 1, 2, ..., n. \tag{18}$$

The price elasticities are presented in table 4. Focusing on R&D, generally the own price elasticities are inelastic, and less than 0.15 percent (in absolute value) for three of the industries. The exception is machinery with an own price elasticity of -1.33 percent. These elasticities are somewhat more inelastic than previous findings, as surveyed by Nadiri and Prucha [2001]. The relatively more inelastic price effects could occur for two reasons; i) all inputs, and not just the capital inputs, are subject to dynamic adjustment effects, and ii) price expectations are not assumed to be constant or static, but are estimated to be rational under *AR(1)* processes. Turning to the cross price elasticities, which show the pattern of substitutes and complements. Typically, R&D capital and labor inputs are substitutes.[17] Next, in industries where R&D and physical capital are complements, R&D and intermediate inputs are also complementary inputs. This is the case for nonelectrical machinery and transportation equipment. Conversely, where R&D and intermediate inputs are substitutes, then the two capital inputs are substitutes, as in the chemical and electrical products industries. The results in this paper show that there are significant cross price effects between R&D capital and the other factors of production.

5. R&D CONTRIBUTION TO PRODUCTIVITY GROWTH

This section calculates and decomposes total factor productivity (TFP) growth in order to derive the contribution of R&D capital. To calculate TFP growth, begin with the general cost function given by (8), $C(\omega_{1t}, ..., \omega_{nt}, y_t, t)$. Since the specification in equation (12) of this function is second order, with time-invariant second order parameters, the cost difference between periods s and t, defined as $c_t - c_s$, consists only of first order terms (see Denny and Fuss [1983], Bernstein and Mohnen [1998]). Thus,

$$c_t - c_s = .5 \sum_{i=1}^{n} \left(\frac{\partial c_t}{\partial \omega_{it}} + \frac{\partial c_s}{\partial \omega_{is}} \right) (\omega_{it} - \omega_{is}) + .5 \left(\frac{\partial c_t}{\partial y_t} + \frac{\partial c_s}{\partial y_s} \right) (y_t - y_s) + .5 \left(\frac{\partial c_t}{\partial t} + \frac{\partial c_s}{\partial s} \right) (t - s). \quad (19)$$

Next, from (9), $Z_i(\omega_{1t}, ..., \omega_{nt}, y_t, t) = \partial c_t / \partial \omega_{it} = z^*_{it}$, $i = 1, ..., n$, where z^*_{it} is the optimized value of z_{it}, and define the mean value as $z^*_{im} = .5(z^*_{it} + z^*_{is})$, (subscript m denotes the mean value of a variable) then collecting terms, (19) becomes:

$$
\begin{aligned}
&.5\left[\sum_{i=1}^{n}\frac{\omega_{it}z_{it}^{*}(z_{it}^{*}-z_{is}^{*})_{im}^{*}}{z_{im}^{*}z_{it}^{*}}+\sum_{i=1}^{n}\frac{\omega_{is}z_{is}^{*}(z_{it}^{*}-z_{is}^{*})z_{im}^{*}}{z_{im}^{*}z_{is}^{*}}\right] \\
&=.5\left(\frac{\partial c_t}{\partial y_t}+\frac{\partial c_s}{\partial y_s}\right)(y_t-y_s)+.5\left(\frac{\partial c_t}{\partial t}+\frac{\partial c_s}{\partial s}\right)(t-s). \qquad (20)
\end{aligned}
$$

Multiplying (20) by -1, adding $(c/y)_m y_m(y_t-y_s)/y_m = .5\,[c_t/y_t+c_s/y_s]\,y_m(y_t-y_s)/y_m$, and collecting terms yields:

$$
\begin{aligned}
&\left(\frac{c}{y}\right)_m y_m\frac{(y_t-y_s)}{y_m}-.5\left[\sum_{i=1}^{n}\frac{s_{it}(z_{it}^{*}-z_{is}^{*})z_{im}^{*}c_t}{z_{im}^{*}z_{it}^{*}}+\sum_{i=1}^{n}\frac{s_{is}(z_{it}^{*}-z_{is}^{*})z_{im}^{*}c_s}{z_{im}^{*}z_{is}^{*}}\right] \\
&=.5\left[(1-\rho_{yt}^{-1})\left(\frac{c}{y}\right)_t+(1-\rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right](y_t-y_s)+.5\,(\xi_{\nu t}c_t+\xi_{\nu s}c_s)\,(t-s), \qquad (21)
\end{aligned}
$$

where $s_{it}=\omega_{it}z_{it}^{*}/c_t$ is the cost share for ith efficiency adjusted factor, $\rho_{yt}=[(\partial c_t/\partial y_t)/(y_t/c_t)]^{-1}$ is the degree of returns to scale, and $\xi_{\nu t}=-(\partial c_t/\partial t)/c_t$ is the input based rate of technological change.

Now efficiency-adjusted *TFP* growth between periods, s and t is defined as,

$$
TFPG^{e}(s,t)=\dot{Y}/Y-(\dot{Z}/Z), \qquad (22)
$$

where

$$
(\dot{Z}/Z)=.5\left[\sum_{i=1}^{n}\frac{s_{it}\,(z_{it}^{*}-z_{is}^{*})}{z_{im}^{*}}\frac{(z_{im}^{*}/y_m)(c/y)_t}{(z_{it}^{*}/y_t)(c/y)_m}+\sum_{i=1}^{n}\frac{s_{is}\,(z_{it}^{*}-z_{is}^{*})}{z_{im}^{*}}\frac{(z_{im}^{*}/y_m)(c/y)_s}{(z_{is}^{*}/y_s)(c/y)_m}\right]
$$

is the efficiency-adjusted input growth rate, and output growth is $\dot{Y}/Y=(y_t-y_s)/y_m$. With this definition, divide (21) by $(c/y)_m y_m$, to obtain the following equation for efficiency-adjusted *TFP* growth:

$$
\begin{aligned}
TFPG^{e}(s,t)&=.5\left[(1-\rho_{yt}^{-1})\left(\frac{c}{y}\right)_t+(1-\rho_{ys}^{-1})\left(\frac{c}{y}\right)_s\right]\frac{\dot{Y}/Y}{(c/y)_m} \\
&+.5\left[\xi_{\nu t}\left(\frac{c}{y}\right)_t y_t+\xi_{\nu s}\left(\frac{c}{y}\right)_s y_s\right]\frac{(t-s)}{(c/y)_m y_m}. \qquad (23)
\end{aligned}
$$

Expression (23) indicates that efficiency-adjusted growth originates from two sources, increasing returns to scale associated with positive output growth, or positive rates of disembodied technical change.[18]

In order to focus on R&D capital, and its contribution to productivity growth, separate the non-R&D components in efficiency-adjusted input growth from the R&D component according to:

$$(\dot{Z}/Z)_N = .5\frac{(\widetilde{c}/y)_m}{(c/y)_m}\left[\sum_{i=1}^{n-1}\frac{\widetilde{s}_{it}\,(z^*_{it}-z^*_{is})}{z^*_{im}}\frac{(z^*_{im}/y_m)(\widetilde{c}/y)_t}{(z^*_{it}/y_t)(\widetilde{c}/y)_m}+\sum_{i=1}^{n-1}\frac{\widetilde{s}_{is}\,(z^*_{it}-z^*_{is})}{z^*_{im}}\frac{(z^*_{im}/y_m)(\widetilde{c}/y)_s}{(z^*_{is}/y_s)(\widetilde{c}/y)_m}\right],$$

where $\widetilde{s}_{it} = \omega_{it}z^*_{it}/\widetilde{c}_t$, $\widetilde{c}_t = \sum_{i=1}^{n-1}\omega_{it}z^*_{it}$ $(i \neq R.)$, and the R&D (or nth) component is provided by:

$$(\dot{Z}/Z)_R = .5\left[\frac{s_{Rt}\,(z^*_{Rt}-z^*_{Rs})}{z^*_{im}}\frac{(z^*_{Rm}/y_m)(c/y)_t}{(z^*_{Rt}/y_t)(c/y)_m}+\frac{s_{Rs}\,(z^*_{Rt}-z^*_{Rs})}{z^*_{Rm}}\frac{(z^*_{Rm}/y_m)(c/y)_s}{(z^*_{Rs}/y_s)(c/y)_m}\right].$$

Therefore, since $(\dot{Z}/Z) = (\dot{Z}/Z)_N + (\dot{Z}/Z)_R$, efficiency-adjusted *TFP* growth, becomes:

$$TFPG^e(s,t) = \dot{Y}/Y - (\dot{Z}/Z)_N - (\dot{Z}/Z)_R \tag{22a}$$

Next, define efficiency-adjusted *TFP* growth between periods, s and t net of R&D, $TFPG^e_n(s,t)$, as:

$$TFPG^e_n(s,t) = \dot{Y}/Y - (\dot{\Xi}/\Xi) \tag{24}$$

where the expression

$$(\dot{\Xi}/\Xi) = (\dot{Z}/Z)_N\frac{(c/y)_m}{(\widetilde{c}/y)_m}$$

is efficiency-adjusted input growth excluding R&D capital. Combining (22a) and (24) establishes the link between the two concepts of efficiency-adjusted productivity growth:

$$TFPG^e_n(s,t) = TFPG^e(s,t) + (\dot{Z}/Z)_R + [(\dot{Z}/Z)_N - (\dot{\Xi}/\Xi)]. \tag{25}$$

Unlike efficiency-adjusted growth, measured or observed *TFP* growth between periods s and t, $TFPG^o_n(s,t)$, is based on observed input growth. Thus observed growth is:

$$TFPG^o_n(s,t) = \dot{Y}/Y - (\dot{\Psi}/\Psi), \tag{26}$$

where

$$(\dot{\Psi}/\Psi) = .5\left[\sum_{i=1}^{n-1}\frac{\widetilde{\varsigma}_{it}\,(v^*_{it}-v^*_{is})}{v^*_{im}}\frac{(v^*_{im}/y_m)(\widetilde{v}/y)_t}{(v^*_{it}/y_t)(\widetilde{v}/y)_m}+\sum_{i=1}^{n-1}\frac{\widetilde{\varsigma}_{is}\,(v^*_{it}-v^*_{is})}{v^*_{im}}\frac{(v^*_{im}/y_m)(\widetilde{v}/y)_s}{(v^*_{is}/y_s)(\widetilde{v}/y)_m}\right]$$

is the observed growth rate of the non-R&D inputs, and $\widetilde{\varsigma}_{it} = w_{it}v_{it}/\widetilde{v}$, $\widetilde{v} = \sum_{i=1}^{n-1} w_{it}v_{it}^*$ ($i \neq R.$). The relationship between observed and efficiency-adjusted *TFP* growth rates is established through expressions (25) and (26):

$$TFPG_n^o(s,t) = TFPG^e(s,t) + (\dot{Z}/Z)_R + [(\dot{Z}/Z)_N - (\dot{\Psi}/\Psi)]. \tag{27}$$

Equation (27) shows that observed *TFP* growth consists of efficiency adjusted growth, an R&D effect, and an adjustment effect that represents the difference between efficiency adjusted and measured growth of non-R&D inputs. Recall that the industries exhibit constant returns to scale, so from equation (23), efficiency-adjusted *TFP* growth consists of disembodied technical change, which can arise from various sources such as the externalities from R&D investment.[19] Thus equation (27) shows that observed non-R&D related productivity growth can occur from external R&D sources through externalities, internal or own R&D investment, and an adjustment effect from changes in factor efficiency.

The productivity results are presented in table 5. Typically, disembodied technical change was a major contributor to productivity growth. The results also show that observed input growth exceeded efficiency-adjusted growth, that is in equation (27), $(\dot{Z}/Z)_N - (\dot{\Psi}/\Psi) < 0$, and therefore the adjustment effect reduced measured productivity growth. This finding is consistent with Bernstein, Mamuneas, and Pashardes [2004], who concluded that since efficiency-adjusted cost shares, which are used to construct $(\dot{Z}/Z)_N$, decline relatively faster for growing and improving inputs, compared to observed cost shares, which are used to construct $\dot{\Psi}/\Psi$, then efficiency-adjusted input growth is generally less than observed input growth. As a consequence, measured productivity growth is less than the efficiency-adjusted rate. Therefore, as found in table 5, a negative adjustment effect ensues.

Turning to the contribution of R&D investment, for all industries R&D was a major component of annual productivity growth. Specifically for the chemical products industry, the main contributor to productivity gains was R&D capital accumulation. Indeed virtually all of observed productivity growth can be accounted for by R&D. R&D contributed 55 percent to annual productivity growth in nonelectrical machinery. This industry only exhibited a negative contribution from R&D for the period 1989-1994. R&D contributed 38 percent to annual productivity growth in electrical products. Although R&D's contribution has continued to decline into the late 1990's, which has been a period of productivity resurgence, R&D investment still accounted for 20 percent of productivity growth. For transportation equipment, R&D accounted for approximately 84 percent of the productivity gains. However, reflecting the relatively cyclical nature of R&D investment in this industry, R&D generated productivity losses in 1979-1983, and 1989-1994. To summarize, in general, with the exception of the period 1979-1983, R&D growth positively and significantly contributed to *TFP* growth.

6. CONCLUSION

The main issue addressed in this paper relates to the estimation of R&D depreciation rates for knowledge intensive industries. The results show that R&D depreciates at an annual rate of; 18 percent for chemical products, 26 percent for nonelectrical machinery, 29 percent for electrical products, and 21 percent for transportation equipment. R&D capital appears to depreciate in about three to five years, at rates that are 2 to 7 times faster than physical capital. With respect to the R&D capital stocks based on the estimated depreciation rates, over the period from 1955 to 1999 the stocks grew by; 143.42 percent for chemical products at an annual rate of 3.26 percent, 106.58 percent for nonelectrical machinery at an annual rate of 2.42 percent, and 86.64 percent for electrical products at an annual rate of 1.97 percent. Due to the cyclical nature of R&D activity in transportation equipment, R&D capital grew by only 8.44 percent, with an annual rate of 0.19 percent.

With the estimated depreciation rates and price expectations generating processes, R&D user costs were calculated. In 1996, which is the reference time period, the user costs were; 0.246 for chemical products, 0.313 for nonelectrical machinery, 0.342 for electrical products, and 0.273 for transportation equipment. These results imply that the (gross of depreciation) marginal returns to R&D capital in nonelectrical machinery and electrical products are equal and exceed the marginal returns in chemical products and transportation equipment.

Estimates of factor price elasticities demonstrated that generally R&D is price inelastic. The pattern of cross price elasticities showed that R&D capital and labor inputs are substitutes, while in industries where R&D and physical capital are complements, R&D and intermediate inputs are also complementary inputs. This is the case for nonelectrical machinery and transportation equipment. Conversely, where R&D and intermediate inputs are substitutes, then the two capital inputs are substitutes, as in the chemical and electrical products industries. These effects have potentially important implications for the evaluation of tax policies on R&D investment and production. First, the existence of complements and substitutes to R&D means that R&D tax incentives can generate significant effects on investment in machinery and equipment and on employment. Second, tax policies aimed at physical capital, such as investment tax credits, and policies targeted to labor, such as payroll taxes, affect R&D investment, especially in R&D intensive industries. These 'cross' effects must be considered for a proper evaluation of tax policies.

R&D investment clearly generated significant productivity gains. With the exception of the period 1979-1983, the results establish that R&D growth considerably contributed to the productivity performance in R&D intensive industries. Specifically for chemical products, essentially all of observed productivity growth can be accounted for by R&D. R&D contributed 55 percent to annual productivity growth in nonelectrical machinery, 38 percent in electrical products, and approximately 84 percent to productivity gains in transportation equipment.

This paper has provided a framework to estimate R&D depreciation rates within the context of intertemporal production decisions. These rates then enable R&D capital, and it's user cost to be more accurately calculated, which in turn fosters the determination of R&D related effects, such as the contribution to productivity growth.

APPENDIX: DATA DESCRIPTION

The data relate to chemical products (SIC 28), nonelectrical machinery (SIC 35), electrical products (SIC 36), and transportation equipment (SIC 37) for the period 1954-2000. Output is produced from four factors of production. These inputs are labor, intermediate inputs, physical capital and R&D capital. All price indices have been normalized to one in 1996, and all quantities are measured in billions of 1996 dollars.

Data on the quantities and price indices of output, labor, intermediate inputs and physical capital were obtained from the Bureau of Labor Statistics (*BLS*).[20] The quantity of output is measured as the value of gross output divided by the output price index. The value of gross output corresponds to shipments plus the change of inventories. The output price deflator index is implicitly defined by a Törnqvist aggregation of two-digit gross outputs.

The labor input is measured in hours, estimated by the *BLS Current Establishment Survey*. It corresponds to the sum of hours of all persons engaged in production in the sector. The price deflator of labor is measured implicitly by dividing the labor compensation by labor hours.

The quantity of intermediate inputs is measured as the total cost of materials, energy, and purchased services divided by the price index of intermediate inputs. The price of intermediate inputs is derived by a Törnqvist index of the price indices of materials, energy, and purchased services, obtained from *BLS*.

Physical capital input is defined as the flow of services of equipment, structures, inventories and land. The stocks of depreciable assets, equipment and structures, is constructed using the perpetual inventory method for declining balance depreciation. The quantity of capital, is measured as the value of capital services divided by the capital price index . The acquisition price of capital before income taxes is defined as $q_K(1-\vartheta_K-\kappa_K)/(1-u_c)$, where q_K is the acquisition price of physical capital measured as a Törnqvist index of the investment price deflators of structures and equipment, $\vartheta = u_c \upsilon_K$, υ_K is the present value of physical capital cost allowances, u_c is the corporate income tax rate, and κ_K is the physical investment tax credit rate obtained from Xanthopoulos (1991). For the period before 1981, the corporate income tax rate was obtained from Auerbach (1983) and Jorgenson and Sullivan (1981); for the period 1981-2000, the rate was obtained from the Office of Technology Assessment (*OTA,* 1995). The present value of capital cost allowances is approximated by $\upsilon_K = \zeta_K(1 - \xi_K \kappa_K)/(\rho + \zeta_K)$, where ζ_K is the capital cost allowance rate constructed as the ratio of capital cost allowances over the capital stock and ρ is the interest rate on Treasury notes of ten-year maturity obtained from *Citibase*. Data on capital cost allowances have been obtained from the Bureau of Economic Analysis (*BEA).* The parameter ξ_K denotes a depreciation base adjustment and takes value 0 except for the 1962-1963 period in which firms had to reduce the depreciable base of the assets by half of the amount of the investment tax credit under the Long Amendment Act.

Since R&D is explicitly introduced as an input, the quantities of labor and intermediate inputs are adjusted for their R&D components in order to avoid double counting. R&D labor cost, i.e., the wages of scientists, engineers, and supporting personnel, has been subtracted from the total labor cost, and the intermediate input component of R&D has been subtracted from the total intermediate input cost. The overhead cost component of R &D weighted by the cost share of labor and intermediate inputs has been subtracted from both labor and intermediate inputs. The R&D cost components as a percentage of R&D expenditures have been obtained from the National Science Foundation (*NSF*), *Research and Development in Industry* (various issues).[21]

The initial R&D capital stock is found by dividing the real R&D expenditures of the year 1953 by the sum of the R&D depreciation rate and the average growth rate of physical capital for the period 1948-1953. The total manufacturing R&D expenditures have been obtained from *Research and Development in Industry* (*NSF*, various issues). The price deflator of R&D capital is constructed as a Törnqvist index of the price deflators of labor and intermediate inputs devoted to research and development. The acquisition price of R&D capital before income taxes is $q_R \left[1 - u_c - \varrho_R\right]/(1 - u_c)$, where q_R is the R&D investment price, ϱ_R is the incremental R&D tax credit, where $\varrho_R = \kappa_R(1 - \xi_R u_c)$, κ_R is the incremental tax credit rate, ξ_R takes the value 0 except for 1989 and 1990-2000 which takes values 0.5

and 1 respectively. The incremental R&D tax credit is constructed by $\kappa_R = g_R\nu$, where $\nu = [1 - \sum_{\tau=1}^{3} .33/(1+\rho)^{\tau}]$ for the period 1982-1989, and after 1990 $\nu = 1 - \varsigma$, where ς is equal to average of 1984-1988 R&D to sales ratio times the inverse of current R&D to sales ratio. For 1981 $\nu = (1 - .5/(1+r) - \sum_{\tau=2}^{3} .33/(1+r)^{\tau}$ since 1982 the base was the average of R&D expenditures for 1980 and 1981. For 1995 and 1996, $v = .5(1-\varsigma)$ since the credit expired in June 1995 and renewed again in June 1996. The statutory rate g_R is equal to 25% for the period 1981 to 1985 and 20% for the period 1986 to 2000.

Table A1: DATA DESCRIPTIVE STATISTICS

Chemical Products (28)				
	Mean	**Std. Dev.**	**Min.**	**Max.**
Output Quantity	177.26	71.49	62.81	302.22
Labor Input	58.70	5.25	47.93	66.22
Physical Capital Input	46.82	22.52	16.62	89.97
Intermediate Inputs	71.28	31.87	25.35	125.08
R&D Expenditures	10.35	4.90	3.36	21.08
Price of Output	0.544	0.291	0.250	1.012
Price of Labor Input	0.458	0.346	0.086	1.139
Price of Phys. Capital Input	0.499	0.272	0.240	1.093
Price of Intermed. Input	0.607	0.298	0.267	1.009
R&D Price	0.511	0.326	0.152	1.078
Nonelectrical *Machinery (35)*				
	Mean	**Std. Dev.**	**Min.**	**Max.**
Output Quantity	138.35	96.70	39.90	423.72
Labor Input	97.56	13.27	67.78	122.72
Physical Capital Input	14.90	9.67	4.10	39.17
Intermediate Inputs	79.12	46.19	22.15	192.31
R&D Expenditures	9.61	4.64	2.64	18.17
Price of Output	0.849	0.281	0.422	1.295
Price of Labor Input	0.468	0.330	0.102	1.152
Price of Phys. Capital Input	0.988	0.208	0.622	1.424
Price of Intermed. Input	0.659	0.274	0.326	1.029
R&D Price	0.531	0.311	0.174	1.058

Table A1 (Cont'd) **:** DATA DESCRIPTIVE STATISTICS

Electrical Products (36)				
	Mean	**Std. Dev.**	**Min.**	**Max.**
Output Quantity	94.95	85.26	19.76	388.69
Labor Input	64.40	9.95	41.60	78.23
Physical Capital Input	31.12	23.92	5.32	88.64
Intermediate Inputs	38.53	28.81	10.14	136.27
R&D Expenditures	13.16	4.54	4.96	26.53
Price of Output	0.974	0.256	0.645	1.342
Price of Labor Input	0.456	0.330	0.111	1.302
Price of Phys. Capital Input	0.490	0.238	0.205	1.042
Price of Intermed. Input	0.880	0.327	0.456	1.400
R&D Price	0.619	0.315	0.234	1.110
Transportation Equipment (37)				
	Mean	**Std. Dev.**	**Min.**	**Max.**
Output Quantity	261.40	92.99	115.51	507.14
Labor Input	86.73	7.41	68.89	98.51
Physical Capital Input	25.36	8.70	12.15	41.58
Intermediate Inputs	128.33	63.49	50.16	309.23
R&D Expenditures	27.32	6.02	15.91	40.87
Price of Output	0.556	0.296	0.220	1.000
Price of Labor Input	0.512	0.354	0.101	1.122
Price of Phys. Capital Input	0.519	0.301	0.026	1.428
Price of Intermed. Input	0.600	0.301	0.232	1.004
R&D Price	0.548	0.330	0.161	1.054

ENDNOTES

[1]These industries also account for 53 percent of manufacturing output.

[2]The production function has the usual properties as described for example in chapter 5 of Mas Collel, Whinston and Green [1995].

[3]It is not possible for h_i $i = 1, ..., n$ to be nonpositive. This would imply nonpositive marginal products in equilibrium, as determined from the first order conditions in equation (6) below. The production function function is also consistent with negative input changes. Negative changes imply declining marginal products, which represent losses due to adjustment costs, or relative factor deterioration.

[4]It is possible to incorporate other forms of depreciation in this model. The model does not restrict the depreciation profile.

[5]As is common, we are assuming that the discount rate is constant (see Nadiri and Prucha [2001], for a survey).

[6]At this point there is no need to specify the expectations generating processes associated with acquisition or hiring prices. The processes need only depend on exogenous variables.

[7]Equation (6) also shows that in equilibrium the efficiency parameters cannot be nonpositive, that is $h_i \nleq 0$, and so $\mu_i \ngeq 1$. Otherwise nonpositive marginal products result.

When $1 > \mu_i > 0\,(h_i > 1)$, to ensure the condition $a\mu_i < 1$ is met, the following must hold (for all positive discount rates ρ):

$$h_i > -1/\rho\,,$$

which is met by default since in this case $h_i > 1$.

When $\mu_i < 0\,(0 < h_i < 1)$, to ensure the condition $a\mu_i > -1$ is met, the following must hold:

$$h_i > 1/(2+\rho)\;,$$

which represents the only constraint on h_i for the condition $|a\mu_i| < 1$ to be satisfied.

[8]The reference time period is 1996. This is the year that price indexes are normalized to unity.

[9]Output measurement error could also be an issue. This has been investigated in a number of papers. Bailey and Gordon [1988], Lichtenberg and Griliches [1989], and Siegel [1995] conclude that the degree of output mismeasurement is relatively constant over time. This result implies that output mismeasurement error does not contribute to productivity growth mismeasurement.

[10]The model was also estimated under the assumption that prices followed second order autoregressive processes. However first order processes could not be rejected as the expectations generating mechanisms.

[11]Additive errors in the factor demand equations reasonably arise from three sources (see for example the survey by Nadiri and Prucha [1998]); measurement errors (such as in acquisition and hiring prices), optimizing errors (producers operate suboptimally), or technological shocks (arising from randomness in the technology).

[12]The inverse of the efficiency parameters were estimated, since they appear as inverses in the first order conditions, (6).

[13]The estimation results under the assumption of $h_i = 1$ are available from the authors. In addition, the parameter estimates are based on constant returns to scale, which could not be rejected. The parameter restrictions for constant returns to scale are $\alpha_i = \alpha_{yy} = \alpha_t = 0$, $i = 1, ..., n$.

[14]The models with *AR(1)* expectations are nested, as are the models with constant price expectations. This feature justifies the use of Likelihood Ratio (LR) tests to determine the preferred specification. The LR statistic has been small sample corrected. The calculation of the LR test statistic is from Sims [1980]. $LR = 2 * (LLU - LLR) * [(T - k)/T]$, where LLU is the *log* of the likelihood function from the unrestricted model, LLR is the *log* of the likelihood from the restricted model, T is the number of observations, and k is the number

of parameters in the unrestricted model divided by the number of equations.

[15]Price expectation equations, (13), were estimated in first differences, because in level form the constants, denoted by the ϕ_i parameters, were insignificant.

[16]For the development of these tests see Breusch and Pagan [1980], and Engle [1984]. The absence of serial correlation for the preferred specification is a further argument in favor of this formulation.

[17]In the electrical products industry, the standard errors associated with the cross price elasticities between R&D and labor are relatively high in relation to the elasticity estimate. Thus the complementary relationship is weak.

[18]Efficiency adjusted *TFP* growth is based on the assumption, following the results of Bailey and Gordon [1988], Lichtenberg and Griliches [1989], Siegel [1995], Bernstein, Mamuneas, Pashardes [2003] that output measurement error does not significantly affect productivity growth.

[19]There has been a great deal of research on R&D externalities or spillovers, see Bernstein and Mohnen [1998], and the references cited therein, as well as the numerous surveys, such as van Pottelsberghe de la Potterie [1997].

[20]For a detailed description and construction of data obtained from BLS, see Gullickson and Harper (1987).

[21]Since the R&D cost components are available only for odd years starting in 1967, the even years have been calculated as an average of the previous and following years. For the years, before 1967, the value of 1967 has been used. In fact R&D cost shares are relatively constant in the years where data is available.

REFERENCES

Auerbach, J. A. (1983). "Corporate Taxation in the United States," *Brookings Papers and Economic Activity*, 2, 451-513.

Bailey, Martin N., and Robert J. Gordon (1988) "The Productivity Slowdown, Measurement Issues, and the Explosion of Computer Power," *Brookings Papers on Economic Activity.*

Ballester, M., M. Garcia-Ayuso, and J. Livnat (2004) "The Economic Value of the R&D Intangible Asset", forthcoming *European Accounting Review*.

Baruch, L., and T. Sougiannis (1999). "Penetrating the book-to-market black box: The R&D effect," *Journal of Business Finance & Accounting*, 26, 419-449.

Bernstein, J. I. and P. Mohnen (1998) "International R&D Spillovers Between U.S. and Japanese R&D Intensive Sectors," *Journal of International Economics*, 44, 315-338.

Bernstein, J. I., Theofanis P. Mamuneas and Panos Pashardes (2003) "Technical Efficiency and U.S. Manufacturing Productivity Growth," Forthcoming *The Review of Economics and Statistics*.

Denny, M. and M. Fuss (1983) "The Use of Discrete Variables in Superlative Index Number Comparisons," *International Economic Review*, 24, 419-421.

Diewert, W. E. (1980) "Aggregation Problems in the Measurement of Capital," in D. Usher, ed., *The Measurement of Capital*, University of Chicago Press, Chicago, U. S. A.

Diewert, W. E. and T. J. Wales (1988) "A Normalized Quadratic Semiflexible Functional Form," *Journal of Econometrics*, 37, 327-342.

Epstein, L. G., and M. Denny (1980) "Endogenous Capital Utilization in a Short-Run Production Model," *Journal of Econometrics*, 12, 189-207.

Griliches, Z. (1979) "Issues in Assessing the Contribution of Research and Development to Productivity Growth." Bell Journal of Economics 10, 92-123.

Griliches, Z. (1990) "Patent Statistics as Economic Indicators: A Survey," *Journal of Economic Literature*, 28, 1661-1707.

Griliches, Z. (1995). "R&D and Productivity: Econometric Results and Measurement Issues," in P. Stoneman ed., *Handbook of the Economics of Innovation and Technological Change,* Blackwell, Oxford, U. K., 52–89.

Gulickson, W. and M. J. Harper (1987) "Multifactor Productivity in U.S. Manufacturing, 1949-83," *Monthly Labor Review*, 110, 18-28.

Hall, B., and J. van Reenen (2000) "How Effective are Fiscal Incentives for R&D? A Review of the Evidence," *Research Policy* 29, 449-470.

Harper, M. J., E. R. Berndt, and D. O. Wood (1989) "Rates of Return and Capital Aggregation Using Alternative Rental Prices," in D. W. Jorgenson and R. Landau eds., *Technology and Capital Formation*, MIT Press, Cambridge, U. S. A.

Hulten, C. R. (1990) "The Measurement of Capital," in E. R. Berndt and J. E. Triplett eds., *Fifty Years of Economic Measurement*, Studies in Income and Wealth, Volume 54, The National Bureau of Economic Research, University of Chicago Press, Chicago, U. S. A.

Hulten, C. R., and F. C. Wykoff (1981) "The Estimation of Economic Depreciation Using Vintage Asset Prices," *Journal of Econometrics*, 15, 367-396.

Hulten, C. R., and F. C. Wykoff (1996) "Issues in the Measurement of Economic Depreciation: Introductory Remarks," *Economic Inquiry*, 34, 10-23.

Jorgenson, D. W. (1989) "Capital as a Factor of Production," in D. W. Jorgenson and R. Landau eds., *Technology and Capital Formation*, MIT Press, Cambridge, U. S. A.

Jorgenson, D. W., and M. A. Sullivan (1981) "Inflation and Corporate Capital Recovery," in C. R. Hulten, ed., *Depreciation, Inflation, and the Taxation of Income from Capital*, Washington, The Urban Institute Press.

Jorgenson, D. W. and Z. Griliches (1967) "The Explanation of Productivity Change," *Review of Economic Studies*, 34, 249-283.

Kollintzas, T., and J. B. Choi (1985) "A Linear Rational Expectations Equilibrium Model of Aggregate Investment With Endogenous Capital Utilization and Maintenance," Department of Economics, University of Pittsburgh, mimeo.

Lichtenberg, Frank R., and Z. Griliches (1989) "Errors of Measurement in Output Deflators," *Journal of Business and Economic Statistics*, 7, 1-9.

Mas-Collel, A., M. Whinston, and J. Green (1995) *Microeconomic Theory*, Oxford University Press, New York, U. S. A.

Nadiri, M.I., and I.R. Prucha, (2001) "Dynamic Factor Demand Models and Productivity Analysis," in E. Dean, M. Harper and C. Hulten (eds.), *New Directions in Productivity Analysis*, Chicago: University of Chicago Press, 103-164.

Nadiri, M. I., and I. R. Prucha (1996) "Estimation of the Depreciation Rate of Physical and R&D Capital in the U. S. Total Manufacturing Sector," *Economic Inquiry*, 34, 43-56.

Office of Technology Assessment (1995) "The Effectiveness of Research and Experimental Tax Credits," *Congress of the United States*.

Pakes, A. and M. Schankerman (1984) "The Rate of Obsolescence of Patents, Research Gestation Lags, and the Private Rate of Return to Research Resources," in Z. Griliches ed., *R&D, Patents, and Productivity,* University of Chicago Press, Chicago, U. S. A.

van Pottelsberghe de la Potterie, B. (1997) "Issues in Assessing the Effect of Interindustry R&D Spillovers," *Economic Systems Research*, **9**, 331-356.

Siegel, D. (1995) "Errors of Measurement and the Recent Acceleration in Manufacturing Productivity Growth," *The Journal of Productivity Analysis,* 6, 297-320.

Xanthopoulos, J. A (1991) *Cost of Capital Model of Effective Tax Rates: Forty Years of Tax Policy and the Effects on Marginal Effective Tax Rates*, Ph.D. Dissertation, University of Maryland.

Table 1: Parameter Estimates

	Chemical Products		*Nonelectrical Machinery*	
Parameter	**Estimate**	**Std. Error**	**Estimate**	**Std. Error**
β_{LL}	-0.00643	0.00753	-0.43703	0.10730
β_{LK}	-0.02552	0.01447	0.04332	0.01001
β_{LR}	0.01156	0.00740	0.31180	0.06022
β_{KK}	-0.10130	0.00775	-0.00429	0.00174
β_{KR}	0.04588	0.01104	-0.03091	0.00549
β_{RR}	-0.02078	0.00906	-0.22246	0.03916
β_{L}	0.76692	0.01741	1.78082	0.05019
β_{LT}	-0.01668	0.00070	-0.02230	0.00135
β_{TT}	0.00065	0.00006	-0.00167	0.00009
β_{K}	0.29782	0.01552	0.07397	0.00641
β_{KT}	-0.00419	0.00062	0.00454	0.00028
β_{R}	0.29348	0.01060	0.33092	0.03419
β_{RT}	-0.00058	0.00035	-0.00075	0.00083
β_{M}	0.46406	0.02184	0.42637	0.03488
β_{MT}	-0.00623	0.00099	0.02133	0.00131
h_L^{-1}	0.19966	0.02015	0.65309	0.03986
h_K^{-1}	0.43714	0.01757	0.21114	0.01528
h_M^{-1}	0.25110	0.02871	0.66945	0.03388
δ_R	0.17611	0.00152	0.25534	0.00316
θ_L	0.37190	0.06997	0.69764	0.06350
θ_K	0.67046	0.04754	0.47238	0.09566
θ_R	0.40228	0.06740	0.65363	0.06107
θ_M	0.41350	0.06795	0.55616	0.05781
System R^2	0.999		0.999	
Log of L.F.	1169.08		1054.84	

Table 1: Parameter Estimates

	Electrical Products		*Transportation Eq.*	
Parameter	**Estimate**	**Std. Error**	**Estimate**	**Std. Error**
β_{LL}	-0.01326	0.02344	-0.26354	0.13664
β_{LK}	0.04729	0.04172	0.04341	0.01119
β_{LR}	-0.00757	0.00331	0.01665	0.06804
β_{KK}	-0.16860	0.02275	-0.01768	0.00267
β_{KR}	0.02698	0.02507	-0.00689	0.00746
β_{RR}	-0.00432	0.00778	-0.04892	0.04780
β_{L}	2.33425	0.02769	0.43437	0.05224
β_{LT}	-0.04565	0.00139	-0.00655	0.00133
β_{TT}	-0.00058	0.00012	0.00044	0.00005
β_{K}	0.27005	0.02544	0.13611	0.00438
β_{KT}	0.00513	0.00115	-0.00172	0.00019
β_{R}	1.22918	0.02518	0.74138	0.02424
β_{RT}	-0.02144	0.00093	-0.00853	0.00079
β_{M}	0.50218	0.01762	0.56708	0.02716
β_{MT}	0.00191	0.00121	-0.00571	0.00095
h_L^{-1}	0.61736	0.04611	0.45089	0.03289
h_K^{-1}	0.38026	0.02438	0.28831	0.03267
h_M^{-1}	0.61677	0.05048	0.77671	0.03136
δ_R	0.28984	0.00420	0.20583	0.00306
θ_L	0.56156	0.06637	0.51250	0.06505
θ_K	0.79817	0.06925	0.62559	0.06071
θ_R	0.55677	0.06356	0.52113	0.05824
θ_M	0.62622	0.06267	0.45404	0.06549
System R^2	0.999		0.998	
Log of L.F.	862.78		1127.25	

Table 2: HYPOTHESIS TESTING

Hypothesis	**Test Stat. (d.f.)**	**Industry** (28)	(35)	(36)	(37)	**Crit. Val.** $\chi^2_{.05}$
No Efficiency Change ($h_i = 1$)	$LR(4)$	183.03	217.99	174.71	206.34	9.49
Constant Expectations	$W(4)$	70.75	47.51	40.44	76.76	9.49
No Efficiency Change ($h_i = 1$) *and Constant Expectations*	$W(8)$	2724.0	1255.2	1992.2	836.2	15.50
1st and 2nd Order Serial Correlation	$LM(128)$	68.61	46.99	57.68	50.28	155.41
1st Order Serial Correlation	$LM(64)$	56.46	41.08	37.72	42.30	83.68
2nd Order Serial Correlation	$LM(64)$	26.30	20.34	23.35	24.50	83.68
Heteroskedasticity (ARCH)	$LM(16)$	21.35	18.79	15.66	16.71	26.30
Concavity	$LR(6)$	9.52	11.27	1.62	—	12.59

Table 3: R&D Stocks and User Costs

(Billions of 1996 $)

Chemical (28)				
	Mean	Std. Dev.	Min.	Max.
R&D Stock ($\delta_R = 10\%$)	76.97	35.85	25.76	157.49
R&D Stock ($\delta_R = 18\%$)	50.77	22.15	24.08	102.37
User Cost ($\delta_R = 10\%$)	0.067	0.042	0.021	0.139
User Cost ($\delta_R = 18\%$)	0.124	0.078	0.038	0.258
Machinery (35)				
	Mean	Std. Dev.	Min.	Max.
R&D Stock ($\delta_R = 10\%$)	73.33	38.88	20.46	133.61
R&D Stock ($\delta_R = 26\%$)	35.44	16.11	16.04	62.79
User Cost ($\delta_R = 10\%$)	0.072	0.044	0.023	0.160
User Cost ($\delta_R = 26\%$)	0.160	0.098	0.052	0.354
Electrical (36)				
	Mean	Std. Dev.	Min.	Max.
R&D Stock ($\delta_R = 10\%$)	102.91	35.58	35.50	177.63
R&D Stock ($\delta_R = 29\%$)	43.30	11.26	27.52	78.33
User Cost ($\delta_R = 10\%$)	0.083	0.043	0.031	0.149
User Cost ($\delta_R = 29\%$)	0.208	0.107	0.079	0.374
Transportation (37)				
	Mean	Std. Dev.	Min.	Max.
R&D Stock ($\delta_R = 10\%$)	240.38	50.25	140.19	306.77
R&D Stock ($\delta_R = 21\%$)	133.03	17.84	109.93	167.81
User Cost ($\delta_R = 10\%$)	0.075	0.048	0.022	0.166
User Cost ($\delta_R = 21\%$)	0.146	0.093	0.042	0.323

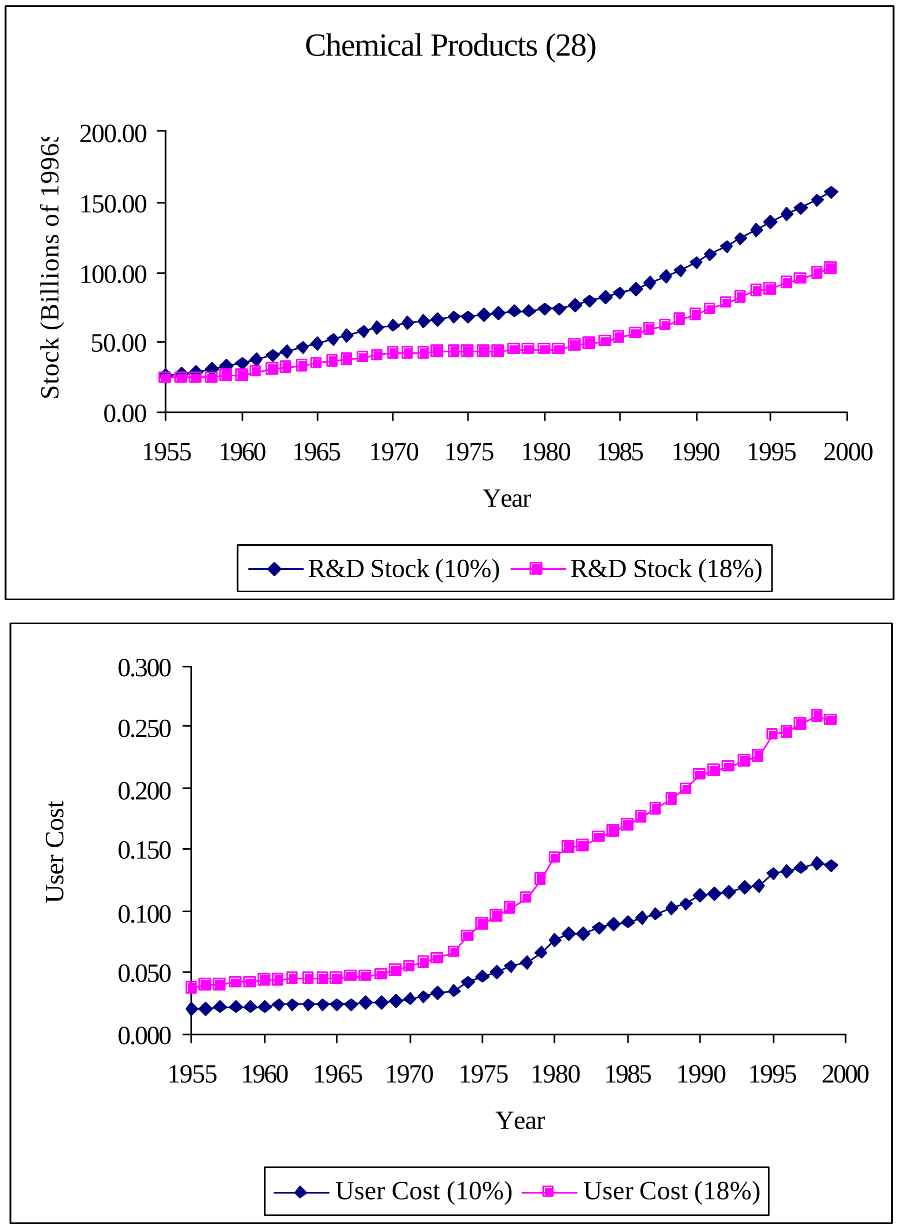


FIG. 1. CHEMICAL PRODUCTS R&D STOCK AND USER COST

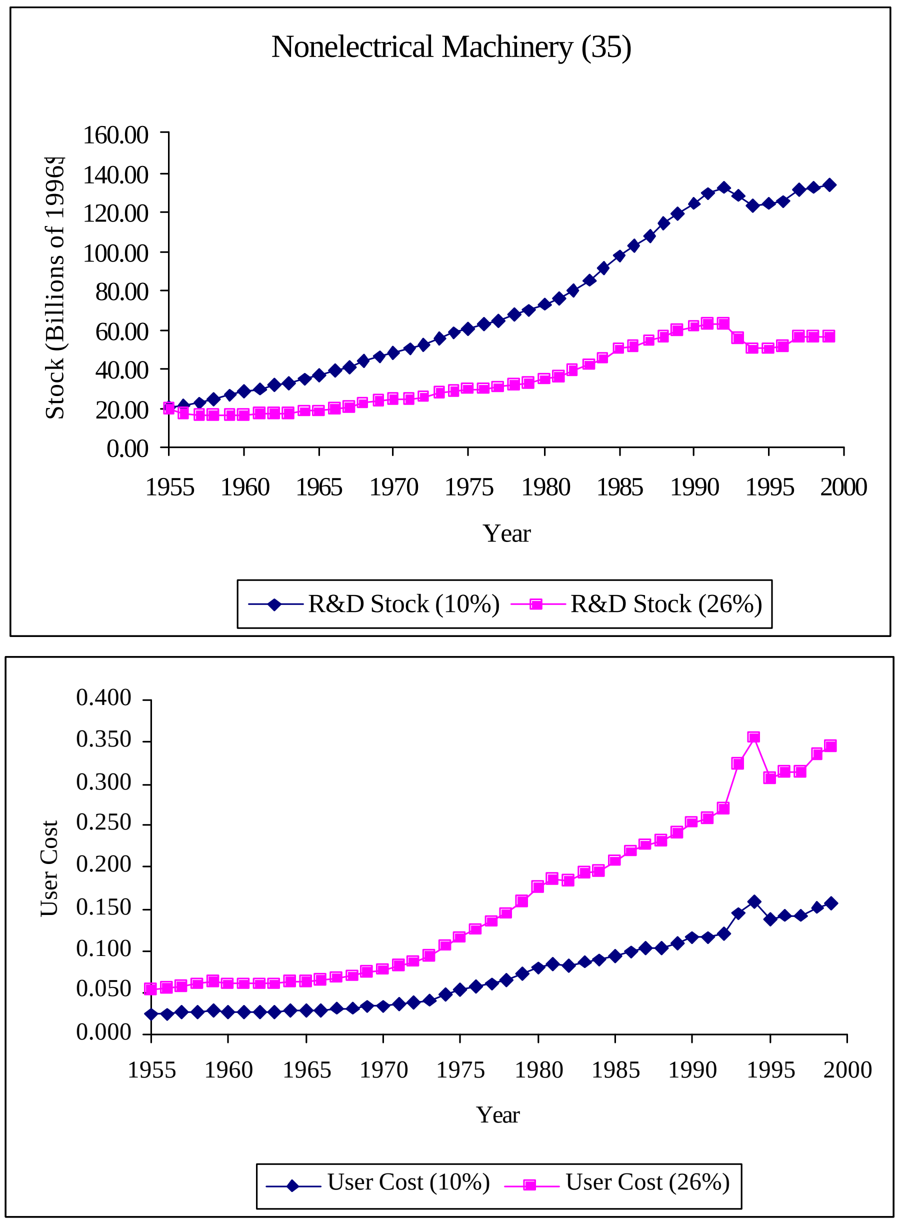


Fig. 2. Nonelectrical Machinery R&D Stock and User Cost

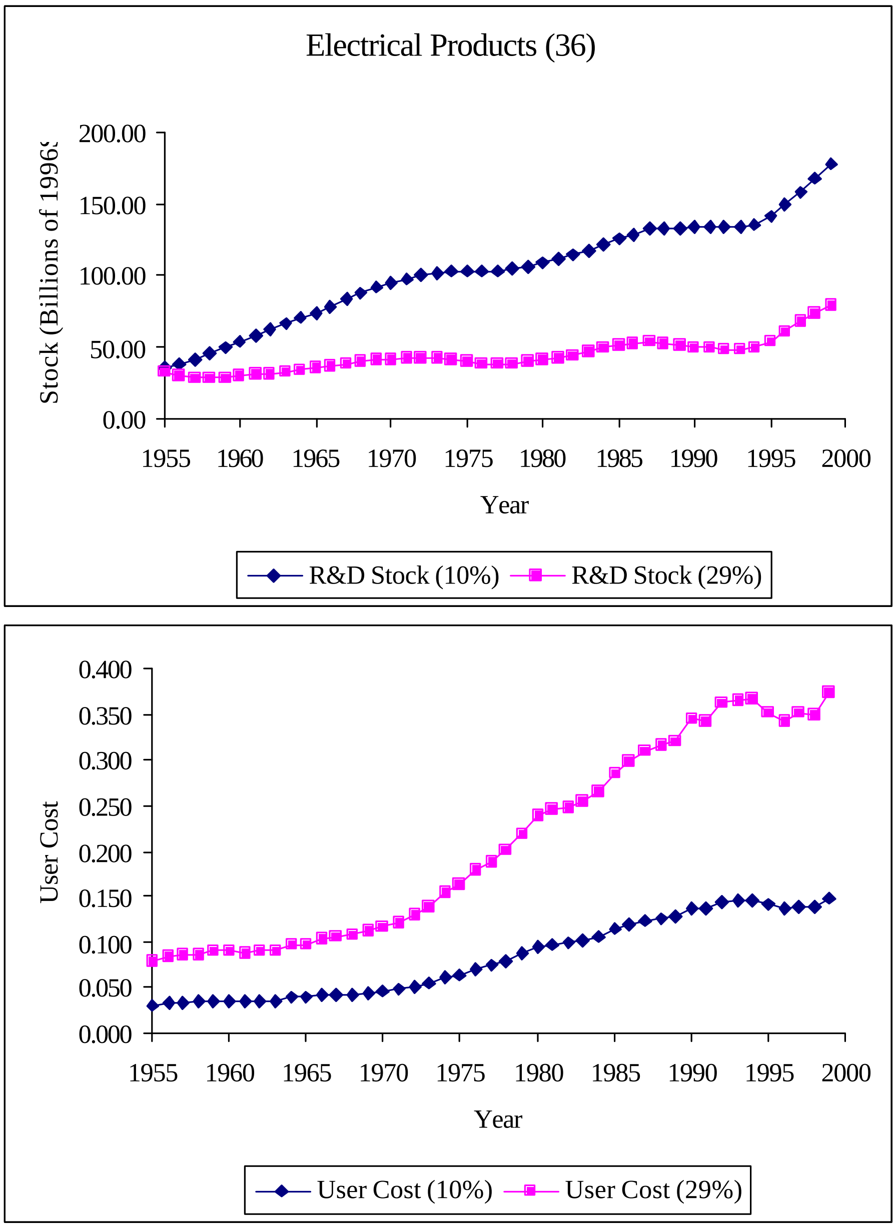
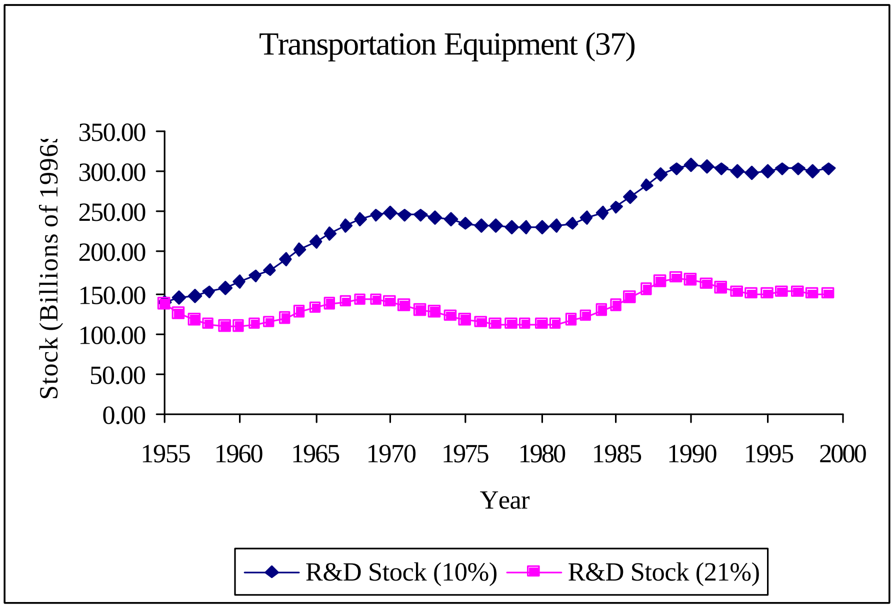


FIG. 3. ELECTRICAL PRODUCTS R&D STOCK AND USER COST



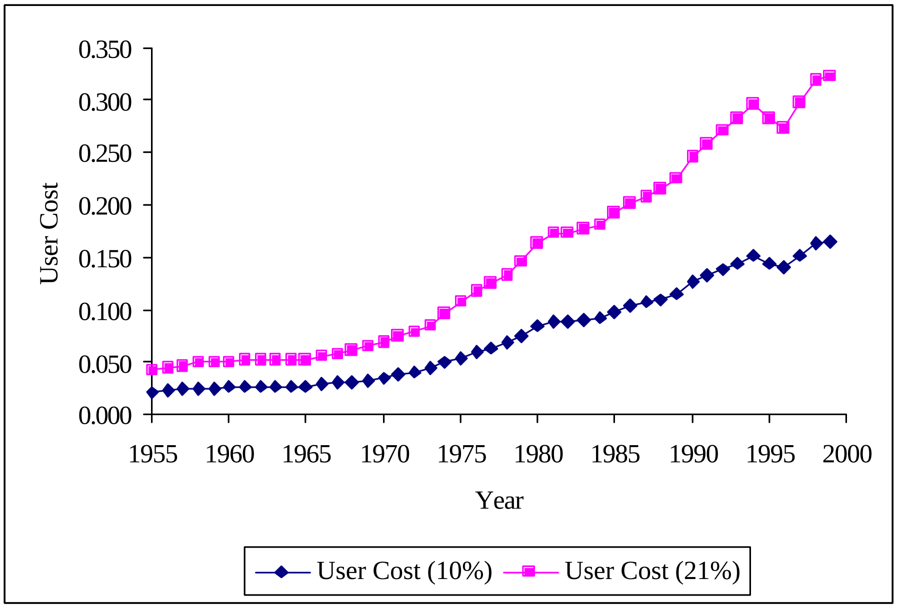


Fig. 4. Transportation Equipment R&D Stock and User Cost

Table 4: Factor Price Elasticities

(Mean Values, Std. Errors in Parenthesis)

Chemical Products (28)				
Quantity of	Price of			
	Labor	Capital	Material	R&D
Labor	-0.0156	-0.0939	0.0401	0.0694
	(0.0012)	(0.0497)	(0.0182)	(0.0429)
Capital	-0.0584	-0.4357	0.1983	0.2958
	(0.0229)	(0.0544)	(0.0460)	(0.0236)
Material	0.0191	0.1536	-0.0709	-0.1018
	(0.0056)	(0.0415)	(0.0261)	(0.0152)
R&D	0.0242	0.1793	-0.0815	-0.1221
	(0.0098)	(0.0188)	(0.0175)	(0.0102)
Nonelectrical Machinery (35)				
Quantity of	Price of			
	Labor	Capital	Material	R&D
Labor	-0.5076	0.1032	-0.4723	0.8767
	(0.0664)	(0.0446)	(0.3993)	(0.0207)
Capital	0.2129	-0.0715	0.2610	-0.4024
	(0.0686)	(0.0279)	(0.0477)	(0.0841)
Material	-0.3385	0.1082	-0.4023	0.6327
	(0.1473)	(0.0375)	(0.0628)	(0.1955)
R&D	0.7191	-0.2188	0.8285	-1.3288
	(0.3690)	(0.0663)	(0.1500)	(0.5290)

Table 4: Factor Price Elasticities

Electrical Products (36)

Quantity of	Price of			
	Labor	Capital	Material	R&D
Labor	-0.0672	0.2299	-0.0633	-0.0993
	(0.0366)	(0.1156)	(0.0278)	(0.0513)
Capital	0.0587	-0.3834	0.1812	0.1435
	(0.0265)	(0.1080)	(0.0765)	(0.0270)
Material	-0.0139	0.0866	-0.0404	-0.0322
	(0.0099)	(0.0381)	(0.0205)	(0.0129)
R&D	-0.0072	0.0372	-0.0154	-0.0146
	(0.0093)	(0.0294)	(0.0083)	(0.0125)

Transportation Equipment (37)

Quantity of	Price of			
	Labor	Capital	Material	R&D
Labor	-0.5648	0.0785	0.4281	0.0582
	(0.2183)	(0.0340)	(0.1639)	(0.0523)
Capital	0.2249	-0.1667	0.0030	-0.0612
	(0.0738)	(0.0694)	(0.1049)	(0.0159)
Material	0.2580	0.0127	-0.5057	0.2350
	(0.0749)	(0.0326)	(0.0526)	(0.0144)
R&D	0.0214	-0.0073	0.1356	-0.1497
	(0.0195)	(0.0020)	(0.0253)	(0.0451)

Table 5: TFP GROWTH DECOMPOSITION

Average Growth Rate in Percent

Chemical Products (28)				
Period	TFP Growth	Tech. Effect	R&D Cont.	Adjust. Effect
1955-1999	0.942	0.388	1.356	-0.803
1955-1973	2.452	0.829	1.990	-0.368
1974-1999	-0.162	0.065	0.893	-1.121
1955-1964	2.941	0.968	2.064	-0.091
1965-1973	1.909	0.675	1.908	-0.674
1974-1978	-3.017	0.415	0.244	-3.677
1979-1983	0.451	0.244	-0.400	0.607
1984-1988	1.504	0.105	2.441	-1.041
1989-1994	-0.271	-0.096	1.014	-1.189
1995-1999	0.545	-0.308	1.144	-0.292
Nonelectrical Machinery (35)				
Period	TFP Growth	Tech. Effect	R&D Cont.	Adjust. Effect
1955-1999	1.879	1.578	1.013	-0.712
1955-1973	0.660	-0.288	0.778	0.170
1974-1999	2.770	2.941	1.184	-1.355
1955-1964	0.415	-0.766	0.364	0.817
1965-1973	0.932	0.244	1.238	-0.550
1974-1978	0.060	1.037	0.566	-1.543
1979-1983	1.310	1.693	0.617	-1.001
1984-1988	5.494	2.532	1.695	1.268
1989-1994	1.370	3.628	-1.250	-1.008
1995-1999	5.893	5.676	4.780	-4.563

Table 5: TFP Growth Decomposition

Electrical Products (36)				
Period	TFP Growth	Tech. Effect	R&D Cont.	Adjust. Effect
1955-1999	2.855	3.519	1.072	-1.736
1955-1973	2.093	1.669	1.864	-1.440
1974-1999	3.411	4.870	0.493	-1.952
1955-1964	2.138	1.431	1.368	-0.661
1965-1973	2.044	1.934	2.416	-2.306
1974-1978	0.189	2.580	0.219	-2.610
1979-1983	1.909	3.176	-0.081	-1.185
1984-1988	3.798	3.953	0.932	-1.088
1989-1994	3.648	5.388	0.033	-1.773
1995-1999	7.463	9.150	1.452	-3.139

Transportation Equipment (37)				
Period	TFP Growth	Tech. Effect	R&D Cont.	Adjust. Effect
1955-1999	0.597	0.894	0.501	-0.798
1955-1973	1.301	1.075	1.014	-0.788
1974-1999	0.082	0.761	0.125	-0.804
1955-1964	2.429	1.130	0.201	1.098
1965-1973	0.047	1.014	1.918	-2.884
1974-1978	-0.192	0.923	0.105	-1.220
1979-1983	0.529	0.844	-2.451	2.135
1984-1988	0.736	0.731	1.889	-1.883
1989-1994	-1.185	0.708	-0.412	-1.481
1995-1999	0.777	0.612	1.603	-1.438