# Productivity and Convergence Trends in the OECD: Evidence from a Normalized Quadratic Variable Profit Function*

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April 27, 2005

## Abstract

This paper empirically investigates aggregate productivity convergence among 15 European Union countries plus Canada and the United States, during the 1960-2002 period. Using a normalized quadratic variable profit function (within a multiple-output and multiple-input framework), we obtain total factor productivity estimates and then test for total factor productivity convergence, using both cross-section and panel data unit root tests. Our results support total factor productivity convergence for all countries. We also find that more countries converge to Germany than the United States, and that within the European Union more countries converge to Germany than France.

*Keywords*: Flexible functional forms; Normalized quadratic variable profit function; Regularity conditions.

*JEL* classification: C22, F33

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*Serletis gratefully acknowledges financial support from the Social Sciences and Humanities Research Council of Canada.

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# 1 Introduction

Typical neoclassical growth models in the tradition of Solow (1956) have the standard implication that, in terms of long-run macroeconomic behavior, poor economies catch up with richer economies. This catching up process has come to be known as the absolute convergence hypothesis. While most of the empirical studies in this literature concentrate on tests of convergence in per capita output (or income), convergence in total factor productivity (TFP) is equally or even more important. Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992) argue that rather than factor accumulation, technological progress and its diffusion are the major sources of economic growth. Dowrick and Nguyen (1989) and Bernard and Jones (1996a) further argue that it is very important to examine technological convergence by focusing on total factor productivity growth instead of convergence in per capita output. If technological convergence does not occur then countries and regions are not catching up, and per capita output growth in rich and poor countries will tend to lead to increased income dispersion.

In this paper we investigate total factor productivity convergence, using data for 17 OECD countries over the period from 1960 to 2002. The countries include 15 European Union countries — Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxemburg, Netherland, Portugal, Spain, Switzerland, and the United Kingdom — plus two North American countries, Canada and the Unites States. The econometric methods that we use in testing the convergence (in total factor productivity) hypothesis fall into two classes. The first class consists of cross-section tests, where we estimate the 'convergence equation,' as in Baumol (1986), Barro and Sala-i-Martin (1991), Islam (1995), and Sala-i-Martin (1996), among others. In this framework, a negative correlation between initial levels of total factor productivity and subsequent growth rates is taken as evidence of convergence.

The second set of convergence tests are based on time series methods. Bernard and Durlauf (1995, 1996) suggest tests that examine the long-run behavior of differences in per capita output (or TFP) across countries. These tests define convergence to mean that these differences are always transitory in the sense that long-run forecasts of output differences between any pair of countries converge to zero as the forecast horizon grows to infinity. According to this approach, convergence requires that output differences between any pair of economies cannot contain unit roots or time trends and that output levels must be cointegrated with a cointegrating vector of (1,-1). The development of panel data unit root tests in recent years facilitates the research on convergence. Along this line, within a panel unit root test framework, productivity levels are said to be converging if differences in productivity levels across countries are stationary processes.

What should be kept in mind is that the above two methods make different assumptions concerning the statistical properties of the data. While cross-section tests assume that the data under analysis are generated by economies far from a steady state, time series tests assume that the data possess well defined population moments in either levels or first differences — see Bernard and Durlauf (1996). That is, the appropriateness of the two sets of tests depends on the property of the data under analysis. In any case, however, it is not an easy task to evaluate whether an economy is near or far from its steady state. In this paper, we use both cross-section tests and two panel data unit root tests — namely, the Im, Pesaran, and Shin (2003) and Taylor and Sarno (1998) tests to evaluate whether (on average) our sample countries are converging or not.

While they are commonly used in empirical studies, cross-section tests and most of the panel unit root tests, including the Im, Pesaran, and Shin (2003) and Taylor and Sarno (1998) tests, are not informative in the sense that they are not capable of determining which countries are converging and which are not. In the case of the panel unit root tests, the problem stems from the joint hypothesis that is tested. Under the joint null hypothesis, rejection of the non-stationary null (or non-convergence null) does not provide information about how many panel members reject the null hypothesis and how many do not. In other words, both the Im, Pesaran, and Shin (2003) and Taylor and Sarno (1998) tests have an 'all or nothing' characteristic where all series are either stationary or non-stationary. Unfortunately, a similar limitation is also associated with the cross-section test. Because of this problem, in this paper we also implement the Breuer, McNown, and Wallace (2001) test as a complementary test to the cross-section test and the two panel unit root tests to identify how many panel members reject the null hypothesis and how many do not.

While the methods of testing for total factor productivity convergence are important, an equally crucial and perhaps more complicated issue is how to estimate total factor productivity. The most commonly used functional forms for the production function are the Cobb-Douglas and the CES, with two inputs — capital and labor. However, these production functions imply serious limitations which may lead to biases in estimating total factor productivity. For example, two of the assumptions underlying the neoclassical growth model in an open economy context are that imports are final goods (openess) and that they are separable from the primary factors (separability). The assumption of openess conflicts with empirical evidence suggesting that the main bulk of imports consists of intermediate goods requiring further processing before delivery to final demand — see Burgess (1974a). The assumption of separability implies that the marginal rate of substitution between capital and labor is independent of the quantity of intermediate inputs. It also implies that the elasticities of substitution between intermediate inputs and either capital or labor are equal. However, most empirical studies suggest that technology is not separable with respect to primary factors and intermediate inputs — see, for example, Burgess (1974).

Hence, imports cannot be omitted from the neoclassical growth model without producing biased estimates. Moreover, by excluding imports and exports from the production function, we ignore the fact that international trade exerts an influence on the mechanism of aggregate productivity convergence through the transmission of technological knowledge and increased competition — see, for example, Dollar, Wolf, and Baumol (1988). Second, these production functions (although regular) suffer from limited flexibility — that is, they have too few parameters to make possible an independent representation of all economically relevant effects. As an example, the Cobb-Douglas production function, restricts the substitution elasticities between all factors and the elasticity of scale and size to unity. Thus, a more flexible functional form is needed in estimating total factor productivity. To address these problems, in this paper we use a Normalized Quadratic (NQ) variable profit function in estimating total factor productivity. The NQ model, introduced by Diewert and Wales (1992), is flexible — that is, capable of approximating an arbitary profit function to the second order — and also allows for the treatment of exports as one of the outputs and that of imports as one of the inputs.

The rest of the paper is organized as follows. Section 2 briefly discusses the NQ variable profit function and the methods for calculating total factor productivity while Section 3 describes the basic total factor productivity convergence and testing procedures. In Section 4 we discuss data issues, estimate the NQ model to obtain total factor productivity, perform the total factor productivity convergence tests, and explore the economic significance of the results. The final section concludes the paper with some suggestions for future research.

## 2 Total Factor Productivity Measurement

As already noted, a flexible functional form that allows for exports and imports is needed in order to obtain correct estimates of total factor productivity. Although there is a large number of commonly used flexible functional forms that satisfy this criterion, such as, for example, the normalized quadratic (NQ), translog, and generalized Leontief variable profit functions, here we choose to use the NQ, because as Diewert and Wales (1987) have shown it possesses the desirable property that correct curvature conditions can be imposed globally without destroying the flexibility of the functional form.

The normalized quadratic variable profit function can be written for $n+1$ goods (including both multiple inputs and multiple outputs) as

$$V(\boldsymbol{p}, k, t) = \sum_{i=1}^{n} a_i p_i + \sum_{i=1}^{n} b_i p_i k + \frac{1}{2} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} \beta_{ij} p_i p_j k}{\sum_{i=1}^{N} \alpha_i p_i} + \sum_{i=1}^{n} c_i p_i k t \quad (1)$$

where $V(\boldsymbol{p}, k, t)$ denotes the variable profit (i.e., gross returns minus variable costs), $\boldsymbol{p} = (p_1, \cdots, p_n)$ with $p_i$ being the price of the $i$th 'output' (with inputs treated as negative outputs), $t$ is the time trend (over the entire sample period), $k$ is the $(n+1)$th good and denotes the minimum amount of fixed capital required to produce the vector of outputs and is assumed to be exogenously given in the short term, and $a$, $b$, $\beta$, $c$, and $\alpha$ are parameters, usually with the $\boldsymbol{\alpha}$ vector ($\boldsymbol{\alpha} > \boldsymbol{0}$) being predetermined. As can be seen, $V(\boldsymbol{p}, k, t)$ in (1) is linearly homogeneous in $\boldsymbol{p}$. Further, we impose two restrictions on the $\boldsymbol{B} \equiv [\beta_{ij}]$ matrix

$$\beta_{ij} = \beta_{ji}, \quad \text{for all } i, j \quad (2)$$

$$\boldsymbol{B}\boldsymbol{p}^* = \boldsymbol{0}, \quad \text{for some } \boldsymbol{p}^* > \boldsymbol{0}. \quad (3)$$

The normalized quadratic variable profit function defined by (1)-(3) is technical progress flexible (TP flexible), as shown by Diewert and Wales (1992). In this paper, we have two outputs (domestic output and exports), three variable inputs (imports, labor and reproducible capital), and one exogenously given input (being an aggregate of land, the stock of inventories, and intellectual property).

Differentiating (1) with respect to prices and using Hotelling's lemma yields a system of net supply functions. By simultaneously estimating the system of net supply functions, we can obtain the estimates of all parameters appearing in (1). Then, differentiating the log of the profit function with respect to $t$, yields an index of total factor productivity for each $t$,

$$A_t = \frac{\nabla_t V\left(\boldsymbol{p}, k, t\right)}{V\left(\boldsymbol{p}, k, t\right)} = \frac{\sum_{i=1}^{n} c_i p_i k}{V\left(\boldsymbol{p}, k, t\right)} \tag{4}$$

## 3 Convergence Model and Test Procedures

After obtaining total factor productivity estimates using the NQ variable profit function, we test the total factor productivity convergence hypothesis using procedures suggested by Bernard and Jones (1996a,b). In particular, we assume that total factor productivity evolves according to

$$\ln A_{it} = \gamma_i + \lambda_i \ln \widehat{A}_{i,t-1} + \ln A_{i,t-1} + \varepsilon_{it} \tag{5}$$

where $A_{it}$ is total factor productivity in country $i$ (at time $t$), $\widehat{A}_{i,t-1}$ is the catch-up variable — the productivity differential with respect to the reference country $i^*$ (i.e., $\widehat{A}_{it} = A_{i^*t}/A_{it}$). $\gamma_i$ is the asymptotic (long-run) growth rate of $A_{it}$, $\lambda_i$ captures the speed of catch-up for country $i$, and $\varepsilon_{it}$ is a country-specific productivity shock.

Equation (5) can be rewritten as[1]

$$\ln \widehat{A}_{it} = \left(\gamma_{i^*} - \gamma_i\right) + \left(1 - \lambda_i\right) \ln \widehat{A}_{i,t-1} + \widehat{\varepsilon}_{it} \tag{6}$$

where $\widehat{\varepsilon}_{it} = \varepsilon_{i^*t} - \varepsilon_{it}$. Equation (6) is the basic model used in this paper, implying that the total factor productivity gap between country $i$ and the reference country $i^*$ is a function of the lagged gap in total factor productivity.

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[1] For the reference country, $i^*$, equation (5) can be written as

$$\ln A_{i^*t} = \gamma_{i^*} + \lambda_{i^*} \ln \widehat{A}_{i^*,t-1} + \ln A_{i^*,t-1} + \varepsilon_{i^*t}$$

Since $\ln \widehat{A}_{i^*,t-1} = 0$, the above equation can be written as

$$\ln A_{i^*t} = \gamma_{i^*} + \ln A_{i^*,t-1} + \varepsilon_{i^*t}$$

Subtracting (5) from the above equation yields equation (6).

In the context of equation (6), if $\lambda_i = 0$ productivity levels will grow at different rates and there is no tendency to catch-up asymptotically. In this case, $\ln \widehat{A}_{it}$ (the difference between total factor productivity levels in the two countries) will contain a unit root. $\lambda_i > 0$ provides an impetus for 'catch-up.' If $\lambda_i > 0$, $\ln \widehat{A}_{it}$ will be stationary.

As we discussed earlier, there are generally two approaches that can be used to test the convergence hypothesis, as represented by (6) — cross-section tests and panel unit root tests — to which we now turn.

## 3.1 The Cross-Section Test

By repeated backward substitution, the difference equation in equation (6) can be written as

$$\begin{aligned}\ln \widehat{A}_{iT} - \ln \widehat{A}_{i0} &= -\left[1-(1-\lambda_i)^T\right] \ln \widehat{A}_{i0} \\ &\quad + \sum_{j=0}^{T} (1-\lambda_i)^{T-j} \left(\gamma_{i^*} - \gamma_i + \widehat{\varepsilon}_i\right) \qquad (7)\end{aligned}$$

where $\ln \widehat{A}_{i0}$ is the productivity differential with respect to the reference country at the beginning of the sample period. Dividing both sides of equation (7) by $T$ yields

$$\overline{g_i} = -\frac{\left[1-(1-\lambda_i)^T\right]}{T} \ln \widehat{A}_{i0} + \frac{1}{T}\sum_{j=0}^{T} (1-\lambda_i)^{T-j} \left(\gamma_{i^*} - \gamma_i + \widehat{\varepsilon}_i\right) \qquad (8)$$

where $\overline{g_i}$ denotes the average growth rate relative to the reference country between time 0 and time $T$. Equation (8) is the familar regression of long-run average growth rates on the initial level. Letting $\beta \equiv -\left[1-(1-\lambda_i)^T\right]/T$, convergence is said to occur if the estimate of $\beta$ is negative and statistically different from 0.

## 3.2 Panel Unit Root Tests

Instead of testing equation (6) in an indirect way as we did in the cross-section test, we can test the null hypothesis of non-convergence in the context of an augmented Dickey-Fuller (ADF) — see Dickey and Fuller (1981) — unit root test as follows

$$\Delta \ln \widehat{A}_{it} = \alpha_i + \rho_i \ln \widehat{A}_{i,t-1} + \sum_{j=1}^{k} c_{ij} \Delta \ln \widehat{A}_{i,t-j} + \widehat{\varepsilon}_{it} \tag{9}$$

where $\alpha_i \equiv (\gamma_{i^*} - \gamma_i)$, $\rho_i = -\lambda_i$, and the $k$ extra regressors have been added to eliminate possible nuisance parameter dependencies of the test statistic caused by temporal dependencies in the disturbances. The optimal lag length, $k$, can be chosen using data-dependent methods that have desirable statistical properties. Testing the null hypothesis of a unit root in the productivity differentials, $H_0 : \rho_i = 0$, is equivalent to testing the null hypothesis of non-convergence in total factor productivity.

A straightforward test procedure is to perform unit root tests for each country. In finite samples, however, unit root tests have low power against alternative hypotheses with highly persistent deviations from equilibrium — see, for example, Levin, Lin, and Chu (2002). To overcome this problem of low test power associated with univariate unit root test procedures, in this paper we implement panel data unit root tests on the productivity differentials. The main advantage of the panel-based unit root test over individual series unit root tests is the increase in power against alternatives. This is because panel data unit root tests combine information from the time-series dimension with that obtained from the cross-sectional dimension.

We apply two panel-based unit root tests to the pooled cross-section time series data of total factor productivity for the 17 OECD countries. The first test, proposed by Im, Pesaran, and Shin (2003), allows for heterogeneity in the value of $\rho_i$ under the alternative hypothesis. The null hypothesis in the Im, Pesaran, and Shin (1997) test can be written as $H_0 : \rho_i = 0$ for $i$ against the alternative hypothesis $H_A : \rho_i < 0$ for $i = 1, 2, ..., N_1$ and $\rho_i = 0$ for $i = N_1 + 1, N_1 + 2, ..., N$. Thus under the null hypothesis, all $\ln \widehat{A}_{it}$ series in the panel are nonstationary processes; under the alternative, a fraction of the series in the panel are assumed to be stationary.

Im, Pesaran, and Shin (2003) propose to use the average of the $t_{\rho_i}$ statistics from a single-country ADF tests to form the following $t$-statistic

$$t\text{-bar} = \frac{\sqrt{N}(\bar{t}_{NT} - \mu_T)}{\sqrt{\sigma_T}},$$

where

$$\bar{t}_{NT} = \frac{1}{N}\sum_{i=1}^{n} t_{\rho_i},$$

and $\mu_T$ and $\sigma_T$ are the mean and variance of each $t_{\rho_i}$ statistic. In fact, $t$-bar is an adjusted group mean of the $t_{\rho_i}$ statistics from single-country ADF tests. The values of $\mu_T$ and $\sigma_T$ for different $T$ and $k$ (number of lags) are tabulated in Im, Pesaran, and Shin (2003, Table 2), based on stochastic simulations. They show that the distribution of $t$-bar weakly converges to a standard normal variate under the null hypothesis that $\rho_i = 0$ for all $i$ and diverges under the alternative hypothesis that $\rho_i < 0$.

A potential problem with the Im, Pesaran, and Shin (2003) procedure involves cross-sectional dependence. In particular, O'Connell (1998) demonstrated that, if the error terms in equation (9) are contemporaneously correlated, size distortion will come in. Recognizing this potential problem, Sarno and Taylor (1998) and Taylor and Sarno (1998) suggest an approach to testing the unit root null hypothesis in panels, which allows both different $\rho$ values under the alternative hypothesis and contemporaneous error correlations across the panel. They call this the multivariate augmented Dickey-Fuller (MADF) test. Following Taylor and Sarno (1998), the panel specification in our particular case (with country $N$ being the reference country) can be written as

$$\begin{aligned}
\Delta \ln \widehat{A}_{1t} &= \alpha_1 + \rho_1 \ln \widehat{A}_{1,t-1} + \sum_{j=1}^{k_1} c_{1j} \Delta \ln \widehat{A}_{1,t-j} + \widehat{\varepsilon}_{1t} \\
&\cdot \\
&\cdot \\
\Delta \ln \widehat{A}_{N-1,t} &= \alpha_{N-1} + \rho_{N-1} \ln \widehat{A}_{N-1,t-1} + \sum_{j=1}^{k_{N-1}} c_{N-1,j} \Delta \ln \widehat{A}_{N-1,t-j} + \widehat{\varepsilon}_{N-1,t}
\end{aligned}$$

In contrast to the Im, Pesaran, and Shin (2003) test, seemingly unrelated estimation is applied to the above system of equations, so that the covariance matrix of the $\varepsilon_{it}$'s is used in estimating each $\rho_i$. Notice that this test also accommodates heterogeneous lags. The null hypothesis that $\rho_i = 0$ for $i$ is tested against the alternative that at least one series is stationary, $\rho_i = 0$. A chi-squared form of Wald statistic is used in the MADF test. However the Wald statistic does not have a chi-squared (with $N$ degrees of freedom) as a limiting distribution, and thus Monte Carlo simulation is need to calculate critical values. Taylor and Sarno (1998) demonstrate that this test has power properties that are significantly better than the single equation augmented Dickey-Fuller test.

### 3.3 Identification Issues

As we mentioned earlier, a problem with most of the panel unit root tests, including both the Im, Pesaran, and Shin (2003) test and the Taylor and Sarno (1998) MADF test, is that while they have the power to reject a false non-convergence null, they do not provide information about how many panel members reject the null hypothesis and how many do not. To address these issues, Breuer, McNown, and Wallace (2001) advocate a panel data unit root test which involves estimating ADF regressions in a seemingly unrelated regression (SUR) framework and then testing for individual unit roots within the panel. The SURADF test is more powerful than independently estimated single equation ADF tests.

Earlier SUR-based tests of O'Connell (1998) and Taylor and Sarno (1998) have an 'all or nothing' characteristic, as all series are either stationary or non-stationary. The Breuer *et al.* (2001) SURADF procedure allows $\rho_i$ to differ across the series under the alternative hypothesis while exploiting information in error covariances to produce efficient estimators with potentially powerful test statistics. Thus, this procedure, which can be viewed as a multivariate version of the Augmented Dickey-Fuller test, allows identification of how many and which members of the panel contain a unit root. The critical values, as in the MADF test case, are specific to the estimated covariance matrix for the system considered, the sample size, and the number of panel members, and thus must be derived through simulations.

## 4 Data and Empirical Evidence

### 4.1 The Data

To obtain total factor productivity estimates, we use annual data for 17 OECD countries over the period from 1960 to 2002. The 17 OECD countries include 15 European Union (EU) countries — Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxemburg, Netherland, Portugal, Spain, Switzerland, and the United Kingdom — plus two North

American countries, Canada and the Unites States. The data consists of prices and quantities for two outputs, three variable inputs, and one exogenously given input. Our treatment of imports as an input to the production sector is standard in this literature — see, for example, Kohli (1991) and Fox and Diewert (1999).

The price and quantity aggregates for (domestic) output are derived from three components — private consumption, government consumption, and investment. The price and quantity data for private and government consumption are from the OECD national accounts, whereas those for investment are constructed using the increase in stocks and gross fixed capital formation prices and quantities both taken from the OECD national accounts. Similarly, the price and quantity data for exports and imports are from the OECD national accounts.

Following Fox (1997), price and quantity aggregates for labor (our fourth input) are derived from two components: wage earners and self employed plus unpaid family workers. The price aggregate, $p_4$, is calculated by dividing the compensation of employees by the number of wage earners, using OECD national accounts data for the former and Labor Force Statistics OECD data for the latter. The price of self employed plus unpaid family workers is taken to be 0.4 times the price of employment, $p_4$. Hence, the compensation of self employed plus unpaid family workers is calculated as $0.4 \times p_4 \times$(civilian employment $-$ wage earners), with the data for civilian employment (that is, total employment) taken from the Labor Force Statistics OECD.

Regarding reproducible capital (our fifth variable, $y_5$), its quantity is calculated as $y_{5t+1} = (1-\delta)y_{5t} + I_t$, with the starting value of $y_5$ being approximated by $I_1 / \left[1 - (1-\delta)/g_I\right]$, where $g_I$ is the average annual growth rate of investment over the sample period and $\delta$ the depreciation rate. Assuming that reproducible capital will depreciate to zero within $T$ years and that the average annual investment growth rate is $g_I$ from (1960-$T$) to 1960, then reproducible capital in 1960 is calculated as

$$\frac{(1-\delta)^T I_1}{g_I^T} + \frac{(1-\delta)^{T-1} I_1}{g_I^{T-1}} + \frac{(1-\delta)^{T-2} I_1}{g_I^{T-2}} + \cdots + I_1 \approx \frac{I_1}{1-(1-\delta)/g_I}.$$

The price of reproducible capital, $p_5$, is calculated as $(R+\delta)p_I$, where $p_I$ is the price of investment, $I$, and $R$ is the ex post rate of return.

Finally, following Diewert (2001) we assume that the exogenously given input, $y_6$, is an aggregate of land, stock of inventories, and intellectual property. We assume that initially land and fixed factors make up half of the residual input and inventories and intellectual capital make up the other half. Assuming that the latter grows at the GDP growth rate, $g_{GDP}$, we set $y_{6t+1} = y_{6t}\left[0.5 + 0.5(1 + g_{GDP})\right]$, with the starting value of $y_6$ (in 1960) approximated by $p_1y_1 + p_2y_2 - p_3y_3 - p_4y_4 - p_5y_5$. Finally, $p_6$ is approximated by $(p_1y_1 + p_2y_2 - p_3y_3 - p_4y_4 - p_5y_5)/y_6$.

## 4.2 Total Factor Productivity Estimates

In estimating total factor productivity for each of the 17 OECD countries (by the maximum likelihood method), we assumed that technology is constant returns to scale, by setting $\boldsymbol{a} = \mathbf{0}$ in equation (1), and also imposed correct convature conditions globally. The total factor productivity estimates obtained using the normalized quadratic variable profit function, equation (1), for each of the 17 OECD countries are shown in Table 1 and Figure 1.

Compared to the total factor productivity estimates reported by Bernard and Jones (1996b) using a Cobb-Douglas production, our estimates differ in two respects. First, Ireland has consistently been the best performer in our study, whereas the United States, which is the productivity leader in Bernard and Jones (1996b), shows only a moderate performance throughout the sample period. Our results are not surpising, and have been confirmed by many previous studies using various different measurement approaches — see, for example, Coe and Helpman (1995). Second, while the total factor productivity estimates for all countries reported by Bernard and Jones (1996) show a general tendency to rise, our estimates show that the patterns of total factor productivity for different countries are quite diverse (see Figure 1). A partial explanation of these differences is that our NQ model is flexible and also allows for multiple outputs and multiple inputs as we discussed earlier, while the Cobb-Douglas production function used by Bernard and Jones (1996b) does not possess these properties. Moreover, different sample periods may be another reason leading to different total factor productivity estimates.

As can be seen in Figure 1, the total factor productivity series for the 17 OECD countries show substantial drop in variance throughout the sample period, providing evidence of convergence in total factor productivity. Roughly speaking, Figure 1 indicates that there are three sets of countries: countries converging from above average (Luxemburg, Denmark, Belgium, Finland, Sweden, the Netherlands, and Ireland), countries converging from below average (Portugal, Spain, Greece, and Canada), and countries that roughly remain at the average level throughout the sample period (Austria, France, Germany, Italy, the United Kingdom, and the United States). This visual evidence of convergence of aggregate total factor productivity is further reinforced by Figure 2, which shows the cross-section standard deviation of total factor productivity. As can be seen from Figure 2, the dispersion has decreased steadily over the sample period from 1.08% in 1960 to 0.42% in 2002. However, formal tests are needed before we come to a conculsion concerning convergence in aggregate total factor productivity for our sample economies during the 1960-2002 period. We now turn to these tests.

## 4.3 Evidence from the Cross-Section Test

We examine the convergence hypothesis, using the cross-section test, for two different panels — a full panel of all 17 OECD countries and an European panel of the 15 European Union countries. A related issue in testing (8) is how to choose benchmark countries. Asymptotically, this choice does not matter, but in small samples it is important. In this paper we choose the largest two economies as the reference country in each panel. In particular, for the full panel of all 17 countries we choose the United States and Germany and for the panel of the 15 European Union countries we choose Germany and France. Ireland is not chosen due to its small economy size although it is the most productive country in our study.

Table 2 reports the results from the cross-section regression of the long-run total factor productivity growth rate relative to the reference country on the total factor productivity differential with respect to the reference country in 1960, as follows

$$\overline{g_i} = \alpha + \beta \ln \widehat{A}_{i,1960} + \eta_i$$

where $\overline{g_i}$ is constructed as the trend coefficient from a regression of the productivity differential with respect to the reference country on a constant and a linear trend — see Bernard and Jones (1996). From the last column of Table 2, we see that all the $R^2$ values are greater than 88%, implying that a very large percentage of the variation in the total factor productivity growth rate relative to the benchmark country can be explained by differences in initial productivity differentials with respect to the benchmark country. Confirming the evidence from standard deviations (see Figure 2), we find a negative and significant coefficient on the initial total factor productivity differential for both panels — the 17 OECD economies and the 15 EU economies

— regardless of the benchmark country. In fact, the point estimates of $\beta$ from the 6 regressions are between -0.0165 and -0.0170, comparable to those reported by Bernard and Jones (1996b), although they employ a different method in estimating total factor productivity and also a different dataset. Correpondingly, the point estimates of $\lambda$, the rates of catch up in total factor productivity, are around 1.25% - 1.30%.

## 4.4 Evidence from Panel Unit Root Tests

Having confirmed the convergence hypothesis using the cross-section test, we now examine the convergence hypothesis for each of the two panels using the Im, Pesaran, and Shin (2003) test and the Taylor and Sarno (1998) MADF test. The benchmark countries are the same as in the cross-section test. Part A of Table 3 reports the results from the Im, Pesaran, and Shin (2003) test. As already noted, to compute the $t$-bar statistic we estimate equation (9) individually for each of the countries in the panel (except for the reference country), and then construct the corresponding ADF $t$-statistics, $t_{\rho_i}$. These individual $t$-statistics are then averaged to obtain the $t$-bar statistic for the panel. The critical values for the $t$-bar statistic of the Im, Pesaran, and Shin (2003) test are from the standard normal distribution.

Part B of Table 3 reports the results from the Taylor and Sarno (1998) MADF test. To calculate the critical values for this tests we first estimate the system of equations using SUR and restrict $\rho_i$ to be equal to zero. We then generate 2000 simulated panel series of $100 + T$ observations using the restricted SUR parameter estimate $\alpha_i$ and $c_{ij}$, we draw randomly from $(0, \widehat{\sum_{\widehat{\varepsilon}}})$, where $\widehat{\sum_{\widehat{\varepsilon}}}$ is the restricted SUR estimate of the contemporanous covariance matrix for the disturbances, and also set the initial values of $\ln \widehat{A}_{1,t-1}$ and $\Delta \ln \widehat{A}_{i,t-j}$ equal to zero. We drop the first 100 observations to yield simulated panel series of $T$ observations, and then order the simulated Wald statistics and use the 20th, 100th, and 200th values as 1%, 5% and 10% critical values, respectively.

Confirming the evidence from the cross-section test, the results in Table 3 show that the null hypothsis of non-convergence (non-stationarity) is rejected for each of the two panels using both the Im, Pesaran, and Shin (2003) and Taylor and Sarno (1998) panel tests. In fact, the $t$-bar statistics of the Im, Pesaran, and Shin (2003) test are well below their respective critical values even at the 1% level and the Wald statistics of the Taylor and Sarno (1998)

MADF test are well above their respective critical values at the 1% level.

## 4.5 Evidence from the Multivariate Test

Having confirmed the convergence hypothesis using both cross-section and panel unit root tests, we now turn to identify the converging countries using the Breuer *et al.* (2001) multivariate test that accounts for cross-sectional dependence among the elements of the panel. Table 4 reports the results for both the OECD panel and the European panel. As with the MADF test, we simulate critical values that are specific to lag structure and the estimated covariance matrix. As we noted earlier, the results from the SURADF tests show that the convergence result found by the cross-section test, the Im, Pesaran, and Shin (2003) test, and the Taylor and Sarno (1998) multivariate augmented Dickey-Fuller test are driven by the convergence behavior of some elements of the panel, not necessarily all of them.

Parts A and B of Table 4 report the results from the SURADF tests for the OECD panel using Germany and the United States as the benchmark countries. There are two interesting findings regarding our SURADF tests for the full OECD panel. First, there are more countries converging to Germany than to the United States. From Part A of Table 4, we can see that there are 8 countries converging to Germany at the 5% level, namely Belgium, Denmark, Italy, Portugal, Spain, Switzerland, the United Kingdom, and the United States. Two more countries (Austria and the Netherlands) can be added to the convergence club if we use the 10% significance level. In contrast, there are only 4 countries converging to the United States at the 5% level, namely Denmark, Germany, Spain, and the United Kingdom. And two more countries (Greece and the Netherlands) are converging to the United States at the 10% level.

Another interesting finding is that Canada does not converge to either of the two benchmark countries. These reults show that convergence is more likely to occur within the EU countries than between EU member countries and the United States. To further investigate the convergence with the 15 European countries, we also perform the SURADF tests for the European panel using Germany and France as benchmark countries. The results are reported in Parts C and D of Table 4. It can be clearly seen that there are 8 countries converging to Germany within the 15 EU countries at the 5% level and two more can be added if we use the 10% significance level. On the other hand, there are only 4 countries converging to France within the

15 EU countries at the 5% level and two more can be added if we use the 10% level. These results show that the convergence club within the 15 EU countries is formed around Germany rather than France.

# 5 Conclusion

We used the normalized quadratic (NQ) variable profit function to estimate total factor productivity using annual data for 15 European Union countries plus Canada and the United States, during the 1960-2002 period. The NQ model is flexible (in the sense that it is capable of approximating an arbitary profit function to the second order).and allows for the estimation of total factor productivity within a multiple-output and multiple-input framework. Moreover, we have treated imports as a separate input and exports as a separate output, thereby allowing for the influence of international trade on aggregate productivity convergence through the transmission of technological knowledge and increased competition.

We also tested for productivity convergence, using methods suggested by Bernard and Jones (1996a,b). In doing so, we applied both cross-section tests ($\beta$-convergence and $\sigma$-convergence) and two panel data unit root tests, proposed by Im, Pesaran, and Shin (2003) and Taylor and Sarno (1998). In general, our results support total factor productivity convergence for all countries. We also applied the multivariate tests proposed by Breuer, McNown, and Wallace (2001) to identify the countries that converge and those that do not. We find that more countries converge to Germany than the United States, and that within the European Union more countries converge to Germany than France.

We have investigated productivity growth, building on a large body of recent literature that takes a flexible functional forms modeling approach. In doing so, we have used the normalized quadratic variable profit function to estimate total factor productivity. Of course, alternative and perhaps more general and more robust specifications could be estimated. A particularly constructive approach would be to use flexible functional forms that possess global properties. One new globally flexible functional form has recently been introduced by Serletis and Shahmoradi (2005). This functional form is based on the Asymptotically Ideal Model (AIM), introduced by Barnett and Jonas (1983) and employed and explained in Barnett, Geweke, and Wolfe (1991). The Serletis and Shahmoradi (2005) AIM($n$)-TP cost function allows for technical progress and for the estimation of total factor productivity, technical progress biases, and related price elasticities.

# References

[1] Aghion, Philippe and Peter Howitt. “A Model of Growth with Creative Destruction.” *Econometrica* 60 (1992), 323-351.

[2] Barnett, William A. and A. Jonas. “The Muntz-Szatz Demand System: An Application of a Globally Well-Behaved Series Expansion.” *Economics Letters* 11 (1983), 337-42.

[3] Barnett, William A., John Geweke, and Michael Wolfe. “Seminonparametric Bayesian Estimation of the Asymptotically Ideal Model.” *Journal of Econometrics* 49 (1991), 5-50.

[4] Baumol, William. “Productivity Growth, Convergence, and Welfare: What the Long-Run Data Show.” *American Economic Review* 76 (1986), 1072-1085.

[5] Barro, Robert J., and Xavier Sala-i-Martin. “Convergence Across States and Regions.” *Brookings Papers on Economic Activity* 1 (1991), 107-158.

[6] Bernard, Andrew B and Steven N. Durlauf, S.N. “Convergence in International Output.” *Journal of Applied Econometrics* 10 (1995), 97-108.

[7] Bernard, Andrew B. and Steven N. Durlauf. “Interpreting Tests of Convergence Hypothesis.” *Journal of Econometrics* 71 (1996a), 161-173.

[8] Bernard, Andrew B. and Charles I. Jones. “Productivity Across Industries and Countries: Time Series Theory and Evidence.” *The Review of Economics and Statistics* 78 (1996b), 135-146.

[9] Breuer, Janice Boucher, Robert McNown, and Myles S. Wallace (2001). “Misleading Inferences in Panel Unit-Root Tests with an Illustration from Purchasing Power Parity.” *Review of International Economics* 9 (2001), 482-493.

[10] Burgess, Frank D. “A Cost Minimization Approach to Import Demand Equations.” *Review of Economics and Statistics* 56 (1974), 225-34.

[11] Coe, David T. and Elhanan Helpman. “International R&D Spillovers.” *European Economic Review* 39 (1995), 859-887.

[12] Dickey, D.A. and W.A. Fuller. "Likelihood Ratio Statistics for Autoregressive Time Series With a Unit Root." *Econometrica* 49 (1981), 1057-1072.

[13] Diewert W. Erwin. "Which (Old) Ideas on Productivity Measurement are Ready to Use?" In *New Developments in Productivity Analysis.* Charles R. Hulten, Edwin R. Dean, and Michael J. Harper (eds.). Chicago: University of Chicago Press (2001), pp. 85-101.

[14] Diewert, W. Erwin and Terence J. Wales. "Flexible Functional Forms and Global Curvature Conditions." *Econometrica* 55 (1987), 43-68.

[15] Diewert, W. Erwin and Terence J. Wales. "A Normalized Quadratic Semi-flexible Functional Form." *Journal of Econometrics* 37 (1988), 327-342.

[16] Diewert, W. Erwin and Terence J. Wales. "Quadratic Spline Models for Producer's Supply and Demand Functions." *International Economic Review* 33 (1992), 705-722.

[17] Dollar, David, Edward N. Wolff, and William J. Baumol. (1988). "The Factor-Price Equalization Model and Industry Labor Productivity: An Empirical Test Across Countries." In Robert C. Feenstra (ed.), *Empirical Methods for International Trade.* MIT Press: Cambridge, MA (1988).

[18] Dowrick, Steve and Duc Tho Nguyen (1989). "OECD Comparative Economic Growth 1950-85: Catch-Up and Convergence." *American Economic Review* 79 (1989), 1010-1030.

[19] Fox, Kevin J. "Open Economy Data Sets for 18 OECD Countries, 1960-1992." University of New South Wales School of Economics, Discussion Paper 1997/26.

[20] Fox, Kevin J. and Diewert W. Erwin. "Is the Asia Pacific Region Different? Technical Progress Bias and Price Elasticity Estimates for 18 OECD Countries, 1960-1992." In *Economic Efficiency and Productivity Growth in the Asia-Pacific Region.* T-T. Fu, C.J. Huang, and C.A.K. Lovell (eds.). Edward Elgar Publishing (1999), pp. 125-144.

[21] Grossman, Gene M., and Elhanan Helpman. "Innovation and Growth in the Global Economy." The MIT Press, Cambridge, MA (1991).

[22] Im, Kyung So, M. Hashem Pesaran, and Yongcheol Shin. "Testing for Unit Roots in Heterogeneous Panels." *Journal of Econometrics* 115 (2003), 53-74.

[23] Islam, N. "Growth Empirics: A Panel Data Approach." *Quarterly Journal of Economics* 110 (1995), 1127-70.

[24] Levin, Andrew, Chien-Fu Lin, and Chia-Shang James Chu (2002). "Unit Root Tests in Panel Data: Asymptotic and Finite-Sample Properties." *Journal of Econometrics* 108 (2002), 1-24.

[25] O'Connell, Paul G. J. "The Overvaluation of Purchasing Power Parity." *Journal of International Economics* 44 (1998), 1-19.

[26] Romer, Paul. "Endogenous Technical Change." *Journal of Political Economy* 98 (1990), 71-102.

[27] Sala-i-Martin, X. "The Classical Approach to Convergence." *Economic Journal* 106 (1996), 1019-1036.

[28] Sarno, Lucio and Mark Taylor. "Real Exchange Rates under the Recent Float: Unequivocal Evidence of Mean Reversion." *Economics Letters* 60 (1998), 131-137.

[29] Serletis, Apostolos and Asghar Shahmoradi. "The Asymptotically Ideal Model and the Estimation of Technical Progress." Mimeo, Department of Economics, University of Calgary (2005).

[30] Taylor, Mark and Lucio Sarno. "The Behavior of Real Exchange Rates During the Post-Bretton Woods Period." *Journal of International Economics* 46 (1998), 281-312.

Table 1: Estimates of TFP for 17 OECD countries (1960-2002)

| | Austria | Belgium | Canada | Denmark | Finland | France | Germany | Greece | Ireland |
|---|---|---|---|---|---|---|---|---|---|
| 1960 | 0.0091 | 0.0175 | 2 0.00224 | 0.02118 | 0.01513 | 0.00387 | 0.00334 | 0.0001 | 0.03906 |
| 1961 | 0.00998 | 0.01666 | 0.00202 | 0.01978 | 0.01467 | 0.00430 | 0.00364 | 0.0002 | 0.03915 |
| 1962 | 0.00996 | 0.01628 | 0.00186 | 0.01929 | 0.01395 | 0.00424 | 0.00382 | 0.00025 | 0.03911 |
| 1963 | 0.01013 | 0.01553 | 0.00134 | 0.01879 | 0.01364 | 0.00463 | 0.00374 | 0.0003 | 0.03942 |
| 1964 | 0.01049 | 0.01555 | 0.00147 | 0.01772 | 0.01438 | 0.00511 | 0.0039 | 0.00008 | 0.04064 |
| 1965 | 0.01069 | 0.01558 | 0.00161 | 0.01689 | 0.01412 | 0.00508 | 0.00402 | 0.00048 | 0.04196 |
| 1966 | 0.01062 | 0.0158 | 0.00167 | 0.01623 | 0.01358 | 0.00507 | 0.00413 | 0.00046 | 0.0424 |
| 1967 | 0.0103 | 0.01544 | 0.00176 | 0.01513 | 0.0132 | 0.00517 | 0.0043 | 0.0006 | 0.04048 |
| 1968 | 0.01001 | 0.01501 | 0.00168 | 0.01448 | 0.01368 | 0.00542 | 0.00439 | 0.00089 | 0.03961 |
| 1969 | 0.00962 | 0.01492 | 0.00158 | 0.01421 | 0.0132 | 0.00542 | 0.00444 | 0.00116 | 0.03927 |
| 1970 | 0.00996 | 0.01473 | 0.00163 | 0.01409 | 0.01261 | 0.00433 | 0.00502 | 0.00093 | 0.03272 |
| 1971 | 0.01014 | 0.0142 | 0.0013 | 0.01328 | 0.01258 | 0.00487 | 0.00504 | 0.00103 | 0.03273 |
| 1972 | 0.00983 | 0.0141 | 0.00141 | 0.01279 | 0.01187 | 0.00533 | 0.00501 | 0.00091 | 0.03284 |
| 1973 | 0.01031 | 0.01409 | 0.00191 | 0.0124 | 0.01141 | 0.00549 | 0.00486 | 0.00122 | 0.0357 |
| 1974 | 0.00949 | 0.01401 | 0.00303 | 0.0124 | 0.00629 | 0.00472 | 0.00474 | 0.00074 | 0.035 |
| 1975 | 0.01023 | 0.01406 | 0.00279 | 0.01262 | 0.0124 | 0.00392 | 0.00531 | 0.00095 | 0.03346 |
| 1976 | 0.01055 | 0.01383 | 0.00283 | 0.01183 | 0.01275 | 0.00557 | 0.00514 | 0.00079 | 0.03907 |
| 1977 | 0.01008 | 0.014 | 0.0024 | 0.01172 | 0.01241 | 0.00449 | 0.00512 | 0.00157 | 0.03699 |
| 1978 | 0.00919 | 0.01387 | 0.00202 | 0.0119 | 0.01227 | 0.00479 | 0.0052 | 0.00165 | 0.03539 |
| 1979 | 0.00974 | 0.01416 | 0.00295 | 0.01135 | 0.01197 | 0.00544 | 0.0053 | 0.00159 | 0.03362 |
| 1980 | 0.00968 | 0.01293 | 0.00391 | 0.01151 | 0.01105 | 0.00538 | 0.0051 | 0.00144 | 0.03134 |
| 1981 | 0.00904 | 0.01277 | 0.00402 | 0.01157 | 0.01084 | 0.00482 | 0.00464 | 0.00208 | 0.03103 |
| 1982 | 0.0086 | 0.01295 | 0.00404 | 0.01134 | 0.01068 | 0.00523 | 0.00474 | 0.0027 | 0.03225 |
| 1983 | 0.00958 | 0.01328 | 0.00404 | 0.01131 | 0.01058 | 0.00459 | 0.0051 | 0.00302 | 0.03466 |
| 1984 | 0.00946 | 0.0134 | 0.0038 | 0.01103 | 0.01075 | 0.00476 | 0.00507 | 0.00272 | 0.03491 |
| 1985 | 0.00942 | 0.01353 | 0.0036 | 0.01077 | 0.01073 | 0.00532 | 0.00502 | 0.00303 | 0.03457 |
| 1986 | 0.00957 | 0.01414 | 0.00329 | 0.0104 | 0.01059 | 0.00589 | 0.00527 | 0.00247 | 0.03446 |
| 1987 | 0.00982 | 0.01409 | 0.00344 | 0.0102 | 0.01044 | 0.00629 | 0.00573 | 0.00311 | 0.03364 |
| 1988 | 0.0096 | 0.01408 | 0.00343 | 0.00999 | 0.01018 | 0.00597 | 0.00574 | 0.0034 | 0.03371 |
| 1989 | 0.00936 | 0.01397 | 0.00354 | 0.01015 | 0.00982 | 0.00577 | 0.00573 | 0.00368 | 0.03376 |
| 1990 | 0.0093 | 0.01392 | 0.00357 | 0.01007 | 0.00987 | 0.00588 | 0.00581 | 0.0037 | 0.02982 |
| 1991 | 0.00928 | 0.01413 | 0.00371 | 0.0099 | 0.01115 | 0.00587 | 0.00706 | 0.00365 | 0.02931 |
| 1992 | 0.00925 | 0.01451 | 0.00378 | 0.01017 | 0.01242 | 0.00611 | 0.00734 | 0.00321 | 0.02787 |
| 1993 | 0.00929 | 0.01506 | 0.00374 | 0.01016 | 0.01316 | 0.00631 | 0.0076 | 0.00317 | 0.02886 |
| 1994 | 0.00929 | 0.01509 | 0.00367 | 0.00989 | 0.01312 | 0.00636 | 0.00775 | 0.00351 | 0.02764 |
| 1995 | 0.00956 | 0.01485 | 0.00398 | 0.00986 | 0.01294 | 0.00644 | 0.00792 | 0.00395 | 0.02581 |
| 1996 | 0.00953 | 0.01482 | 0.00407 | 0.00982 | 0.01259 | 0.00652 | 0.00799 | 0.00422 | 0.02428 |
| 1997 | 0.00956 | 0.01481 | 0.00392 | 0.00986 | 0.01175 | 0.00666 | 0.00804 | 0.00466 | 0.0225 |
| 1998 | 0.00954 | 0.01492 | 0.00362 | 0.00963 | 0.01122 | 0.00654 | 0.00815 | 0.00432 | 0.02138 |
| 1999 | 0.00959 | 0.0148 | 0.00363 | 0.00932 | 0.01068 | 0.00649 | 0.00831 | 0.00426 | 0.019 |
| 2000 | 0.00947 | 0.01478 | 0.00393 | 0.00948 | 0.01009 | 0.00632 | 0.00839 | 0.00417 | 0.01812 |
| 2001 | 0.00959 | 0.01505 | 0.00381 | 0.00942 | 0.01006 | 0.0064 | 0.00854 | 0.00471 | 0.01768 |
| 2002 | 0.00975 | 0.01541 | 0.00364 | 0.00895 | 0.00992 | 0.00659 | 0.00875 | 0.00511 | 0.017 |

Table 1: continued

| | Italy | Luxemburg | NL | Portugal | Spain | Switzerland | U.K. | U.S. | STDEV |
|---|---|---|---|---|---|---|---|---|---|
| 1960 | 0.01316 | 0.03309 | 0.01281 | 0.00591 | 0.00101 | 0.01428 | 0.01056 | 0.00886 | 0.01078 |
| 1961 | 0.0131 | 0.02941 | 0.01281 | 0.00637 | 0.00132 | 0.01391 | 0.01083 | 0.00884 | 0.01020 |
| 1962 | 0.0125 | 0.02806 | 0.01216 | 0.00661 | 0.0015 | 0.01296 | 0.01099 | 0.00843 | 0.00998 |
| 1963 | 0.01249 | 0.02461 | 0.01214 | 0.00757 | 0.00179 | 0.01243 | 0.01067 | 0.00801 | 0.00964 |
| 1964 | 0.01341 | 0.02250 | 0.01126 | 0.00626 | 0.00227 | 0.01180 | 0.01061 | 0.00745 | 0.00968 |
| 1965 | 0.01251 | 0.02292 | 0.01099 | 0.00632 | 0.00375 | 0.01150 | 0.01062 | 0.00712 | 0.00998 |
| 1966 | 0.01236 | 0.02262 | 0.01049 | 0.00595 | 0.00601 | 0.01108 | 0.01068 | 0.00683 | 0.00976 |
| 1967 | 0.01204 | 0.02257 | 0.01015 | 0.00532 | 0.00807 | 0.01084 | 0.01081 | 0.0069 | 0.00927 |
| 1968 | 0.01166 | 0.02345 | 0.0098 | 0.0083 | 0.00897 | 0.01087 | 0.01031 | 0.00656 | 0.00903 |
| 1969 | 0.01134 | 0.02273 | 0.00881 | 0.00898 | 0.00923 | 0.01069 | 0.01042 | 0.00645 | 0.00888 |
| 1970 | 0.01152 | 0.02462 | 0.00868 | 0.00814 | 0.00884 | 0.01064 | 0.0108 | 0.00652 | 0.00788 |
| 1971 | 0.01176 | 0.02134 | 0.00767 | 0.00885 | 0.00922 | 0.01075 | 0.01104 | 0.00641 | 0.00751 |
| 1972 | 0.01206 | 0.02015 | 0.00733 | 0.00874 | 0.00972 | 0.01038 | 0.01134 | 0.00591 | 0.00743 |
| 1973 | 0.01065 | 0.02098 | 0.00734 | 0.00853 | 0.00948 | 0.01025 | 0.01005 | 0.00554 | 0.00798 |
| 1974 | 0.01046 | 0.02203 | 0.00725 | 0.00996 | 0.00776 | 0.01055 | 0.00916 | 0.00502 | 0.00804 |
| 1975 | 0.01126 | 0.02089 | 0.00812 | 0.01042 | 0.00869 | 0.01087 | 0.01051 | 0.00519 | 0.00756 |
| 1976 | 0.01059 | 0.02133 | 0.00747 | 0.00961 | 0.0096 | 0.01085 | 0.01004 | 0.00509 | 0.00864 |
| 1977 | 0.01079 | 0.01781 | 0.00833 | 0.00938 | 0.00947 | 0.01076 | 0.00996 | 0.0047 | 0.00800 |
| 1978 | 0.01051 | 0.01748 | 0.00784 | 0.00957 | 0.01086 | 0.01047 | 0.0103 | 0.00452 | 0.00767 |
| 1979 | 0.01036 | 0.01781 | 0.007 | 0.00923 | 0.01151 | 0.01035 | 0.01048 | 0.0043 | 0.00728 |
| 1980 | 0.01012 | 0.01846 | 0.00689 | 0.00853 | 0.01011 | 0.01017 | 0.01128 | 0.00402 | 0.00682 |
| 1981 | 0.0101 | 0.01981 | 0.00625 | 0.00802 | 0.00933 | 0.01023 | 0.01179 | 0.00428 | 0.00689 |
| 1982 | 0.01053 | 0.02126 | 0.00791 | 0.00816 | 0.00965 | 0.01009 | 0.01182 | 0.00496 | 0.00711 |
| 1983 | 0.01077 | 0.01969 | 0.00813 | 0.00794 | 0.00885 | 0.01006 | 0.01172 | 0.00532 | 0.00743 |
| 1984 | 0.01073 | 0.01795 | 0.0074 | 0.00829 | 0.00913 | 0.01006 | 0.01175 | 0.00515 | 0.00740 |
| 1985 | 0.01081 | 0.01787 | 0.00794 | 0.00882 | 0.01026 | 0.01001 | 0.01159 | 0.00516 | 0.00726 |
| 1986 | 0.01117 | 0.01711 | 0.00812 | 0.01033 | 0.01218 | 0.00992 | 0.01155 | 0.00501 | 0.00723 |
| 1987 | 0.01126 | 0.01632 | 0.00723 | 0.01033 | 0.01209 | 0.00982 | 0.0114 | 0.00482 | 0.00696 |
| 1988 | 0.01139 | 0.01396 | 0.00639 | 0.01005 | 0.01221 | 0.00991 | 0.011 | 0.00471 | 0.00690 |
| 1989 | 0.0116 | 0.01330 | 0.00661 | 0.01081 | 0.01216 | 0.00995 | 0.01099 | 0.00466 | 0.00688 |
| 1990 | 0.01185 | 0.01254 | 0.0065 | 0.0111 | 0.01264 | 0.00975 | 0.0117 | 0.00468 | 0.00605 |
| 1991 | 0.01215 | 0.01212 | 0.00646 | 0.01216 | 0.0134 | 0.00994 | 0.01265 | 0.0049 | 0.00594 |
| 1992 | 0.01231 | 0.01222 | 0.00633 | 0.01291 | 0.01449 | 0.01026 | 0.01337 | 0.00483 | 0.00579 |
| 1993 | 0.01275 | 0.01230 | 0.00626 | 0.01346 | 0.0154 | 0.01088 | 0.01349 | 0.0048 | 0.00607 |
| 1994 | 0.01279 | 0.01259 | 0.00625 | 0.01415 | 0.01546 | 0.01097 | 0.01322 | 0.0047 | 0.00585 |
| 1995 | 0.0128 | 0.01277 | 0.00627 | 0.01464 | 0.01526 | 0.01088 | 0.01285 | 0.0046 | 0.00545 |
| 1996 | 0.01291 | 0.01300 | 0.00602 | 0.01446 | 0.01526 | 0.01084 | 0.0127 | 0.00453 | 0.00516 |
| 1997 | 0.01291 | 0.01247 | 0.00595 | 0.01446 | 0.0149 | 0.01082 | 0.01283 | 0.00446 | 0.00481 |
| 1998 | 0.01284 | 0.01247 | 0.00579 | 0.01388 | 0.01499 | 0.01064 | 0.01303 | 0.0043 | 0.00471 |
| 1999 | 0.01279 | 0.01201 | 0.00533 | 0.01402 | 0.01442 | 0.01031 | 0.01313 | 0.00412 | 0.00438 |
| 2000 | 0.01256 | 0.01179 | 0.00539 | 0.01403 | 0.01381 | 0.01041 | 0.01303 | 0.00392 | 0.00422 |
| 2001 | 0.01266 | 0.01169 | 0.00546 | 0.01468 | 0.01387 | 0.01061 | 0.01326 | 0.004 | 0.00419 |
| 2002 | 0.01308 | 0.01137 | 0.00547 | 0.01552 | 0.01398 | 0.01035 | 0.0134 | 0.00401 | 0.00420 |

## Figure 1. Total Factor Productivity Estimates for 17 OECD Countries (1960-2002)

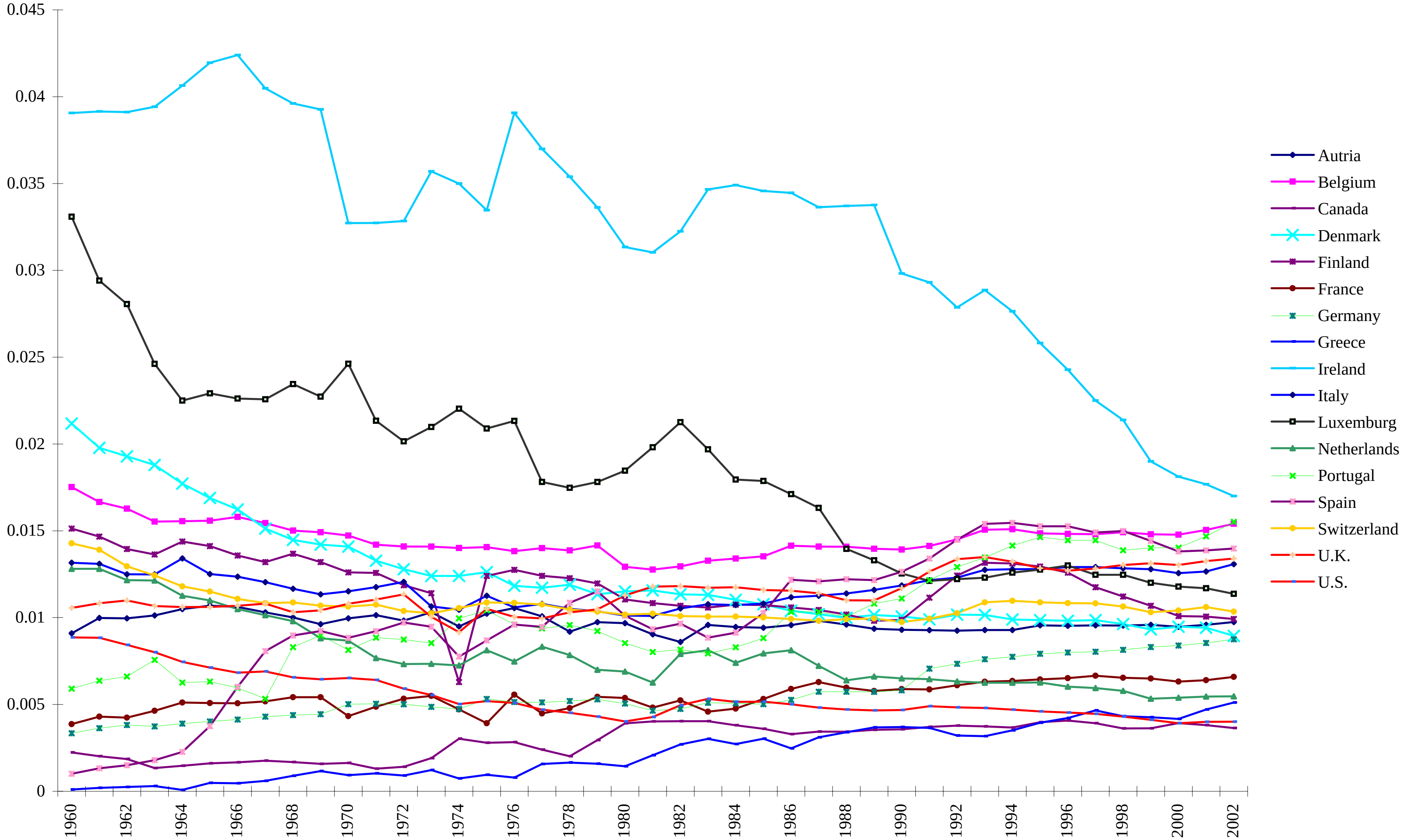

Figure 2: Standard Deviation of Aggregate TFP for 17 OECD Countries (1960 - 2002)

## Table 2: Cross-section Convergence Tests

| Panel | Benchmark country | $\beta$ | $t$-statistic | $p$-value | $\lambda$ | $R^2$ |
|---|---|---|---|---|---|---|
| 17 OECD countries | Germany | $-0.016662$ | $-10.68$ | $\leq 0.001$ | 0.012643 | 0.8828 |
| | United States | $-0.016500$ | $-12.77$ | $\leq 0.001$ | 0.012547 | 0.9153 |
| 15 EU countries | Germany | $-0.016541$ | $-11.34$ | $\leq 0.001$ | 0.012572 | 0.9076 |
| | France | $-0.016947$ | $-12.80$ | $\leq 0.001$ | 0.012811 | 0.9261 |

## Table 3: Panel Unit Root Tests

### A. Im, Pesaran, and Shin (2003) tests

| Panel | Benchmark Country | $T$-bar | Critical Values |  |  | $p$-value |
|---|---|---|---|---|---|---|
|  |  |  | 10% | 5% | 1% |  |
| 17 OECD countries | Germany | -2.181 | -1.78 | -1.85 | -1.98 | $\leq 0.001$ |
|  | United States | -2.207 | -1.78 | -1.85 | -1.98 | $\leq 0.001$ |
| 15 EU countries | Germany | -2.325 | -1.81 | -1.89 | -2.05 | $\leq 0.001$ |
|  | France | -2.105 | -1.81 | -1.89 | -2.05 | $\leq 0.001$ |

### B. Taylor and Sarno (1998) MADF tests

| Panel | Benchmark Country | Wald | Critical Values |  |  |
|---|---|---|---|---|---|
|  |  |  | 10% | 5% | 1% |
| 17 OECD countries | Germany | 212.3 | 169.2 | 181.8 | 209.8 |
|  | United States | 224.1 | 168.6 | 181.0 | 207.9 |
| 15 EU countries | Germany | 212.3 | 167.1 | 180.1 | 206.2 |
|  | France | 200.4 | 141.0 | 153.8 | 184.4 |

## TABLE 4: SURADF TESTS

A. All 17 OECD countries: Germany is the benchmark

| | SURADF | 1% | 5% | 10% |
|---|---|---|---|---|
| Austria | −4.177* | −5.216 | −4.475 | −4.066 |
| Belgium | −6.491* | −6.136 | −5.384 | −4.998 |
| Canada | −1.623 | −4.695 | −4.015 | −3.665 |
| Denmark | −6.500* | −6.081 | −5.303 | −4.916 |
| Finland | −2.050 | −4.289 | −3.601 | −3.252 |
| France | −2.301 | −4.686 | −3.977 | −3.625 |
| Greece | −1.441 | −4.145 | −3.450 | −3.119 |
| Ireland | −2.250 | −5.525 | −4.802 | −4.449 |
| Italy | −5.690* | −5.597 | −4.910 | −4.524 |
| Luxemburg | −3.829 | −5.258 | −4.611 | −4.210 |
| Netherlands | −3.431** | −4.527 | −3.771 | −3.404 |
| Portugal | −5.710* | −4.328 | −3.665 | −3.279 |
| Spain | −7.214* | −4.900 | −4.189 | −3.790 |
| Switzerland | −7.192* | −6.394 | −5.699 | −5.309 |
| U.K. | −4.668* | −5.228 | −4.484 | −4.105 |
| U.S. | −5.016* | −5.532 | −4.829 | −4.464 |

B. All 17 OECD countries: U.S. is the benchmark

| | SURADF | 1% | 5% | 10% |
|---|---|---|---|---|
| Austria | −3.049 | −4.612 | −3.960 | −3.584 |
| Belgium | −2.097 | −5.327 | −4.668 | −4.277 |
| Canada | −0.618 | −4.818 | −4.176 | −3.783 |
| Denmark | −5.233* | −5.185 | −4.448 | −4.050 |
| Finland | −3.216 | −4.281 | −3.654 | −3.275 |
| France | −2.139 | −4.314 | −3.670 | −3.320 |
| Germany | −3.991* | −4.376 | −3.708 | −3.324 |
| Greece | −3.440** | −4.385 | −3.721 | −3.370 |
| Ireland | −1.019 | −4.451 | −3.800 | −3.442 |
| Italy | −3.118 | −5.375 | −4.708 | −4.323 |
| Luxemburg | −2.496 | −4.709 | −4.003 | −3.631 |
| Netherlands | −3.149** | −3.893 | −3.259 | −2.912 |
| Portugal | −1.483 | −4.432 | −3.763 | −3.419 |
| Spain | −8.805* | −4.621 | −3.933 | −3.552 |
| Switzerland | −1.480 | −5.470 | −4.755 | −4.353 |
| U.K. | −4.283* | −4.949 | −4.273 | −3.890 |

Note: An * indicates significance at the 5% level. ** indicates significance at the 10% level.

## Table 4: CONTINUED

C. 15 EU countries: Germany is the benchmark

| | SURADF | 1% | 5% | 10% |
|---|---|---|---|---|
| Austria | −4.449* | −5.012 | −4.306 | −3.952 |
| Belgium | −6.408* | −5.891 | −5.195 | −4.814 |
| Denmark | −6.591* | −5.793 | −5.137 | −4.752 |
| Finland | −1.520 | −4.035 | −3.384 | −3.053 |
| France | −2.713 | −4.496 | −3.818 | −3.450 |
| Greece | −1.045 | −3.890 | −3.279 | −2.985 |
| Ireland | −2.663 | −5.322 | −4.708 | −4.347 |
| Italy | −5.755* | −5.338 | −4.694 | −4.311 |
| Luxemburg | −4.163** | −5.003 | −4.337 | −3.951 |
| Netherlands | −3.794** | −4.495 | −3.804 | −3.464 |
| Portugal | −5.488* | −4.118 | −3.474 | −3.139 |
| Spain | −7.273* | −4.647 | −3.938 | −3.565 |
| Switzerland | −7.128* | −6.130 | −5.407 | −5.075 |
| U.K. | −4.711* | −5.062 | −4.344 | −3.986 |

D. 15 EU countries: France is the benchmark

| | SURADF | 1% | 5% | 10% |
|---|---|---|---|---|
| Austria | −3.691 | −6.274 | −5.648 | −5.285 |
| Belgium | −5.802** | −6.668 | −6.115 | −5.745 |
| Denmark | −2.322 | −5.037 | −4.364 | −3.970 |
| Finland | −5.723** | −6.600 | −5.939 | −5.582 |
| Germany | −2.075 | −5.787 | −5.090 | −4.707 |
| Greece | −2.001 | −4.224 | −3.621 | −3.299 |
| Ireland | −0.403 | −5.794 | −5.115 | −4.738 |
| Italy | −6.313* | −6.380 | −5.768 | −5.423 |
| Luxemburg | −2.057 | −5.652 | −5.024 | −4.623 |
| Netherlands | −3.166 | −6.080 | −5.436 | −5.051 |
| Portugal | −3.323 | −5.136 | −4.422 | −4.010 |
| Spain | −9.010* | −5.526 | −4.771 | −4.363 |
| Switzerland | −6.161* | −6.617 | −5.976 | −5.643 |
| U.K. | −5.778* | −6.123 | −5.480 | −5.115 |

Note: An * indicates significance at the 5% level. ** indicates significance at the 10% level.