Title: NETWORK EXTERNALITIES AND THE INTERNET

Running title: Internet Network Externalities

Russel Cooper
School of Economics and Finance
Building BB, Werrington South
University of Western Sydney
Locked Bag 1797
South Penrith DC NSW 1797
Tel: + 61-2-8255-6233, Fax: + 61-2-8255-6222

Gary Madden*
Communication Economics and Electronic Markets Research Centre
School of Economics and Finance
Curtin University of Technology
GPO Box U1987, Perth, Australia 6845
Tel: +61-8-9266-4258, Fax: +61-8-9266-2391

*Corresponding author. The authors would like to thank James Alleman for helpful comments. Assistance by Grant Coble-Neal and data collection by Michael Schipp are gratefully acknowledged. The usual disclaimer applies.

Network Externalities and the Internet

Abstract

A driving force behind the emergence of the "new" or information economy is the growth of Internet network capacity. A fundamental problem in mapping this dynamic is the lack of an acceptable theoretical framework through which to direct empirical investigations. Most of the models in the literature on network externalities have been developed in a static framework, with externalities viewed as instantaneous or self-fulfilling. The model specified here builds on received theory from several sources to include these features and develops a model that is both capable of econometric estimation and which provides as an output a direct measure of the network effect. Accordingly, the main goal of this paper is to find the magnitude of the external effect on Internet network growth. In addition, this paper illustrates the ability of panel data to generate estimates of structural parameters capable of explaining Internet host growth.

I. INTRODUCTION

The Internet is a distribution system or conduit through which content is sent. Traditional telecommunications systems are specialized in that they (essentially) carry only two-way simultaneous voice along dedicated circuit-switched paths and it is not easily modified to do much else (Economides and White, 1994). What is different (and unique) about the Internet network is that it is both broadband two-way and interactive. Just about any electronic signal can be sent, more or less, from anybody to anybody else (Faulhaber, 1999). Another distinguishing feature of Internet traffic is that it is packet-switched, i.e., no continuous path is devoted to the delivery of a message.

Recent Internet network growth is creating markets for broadband (bandwidth) capacity to carry such high-speed data transfers. Accordingly, the Internet has the potential to increase productivity growth and generate wealth in a variety of distinct but mutually reinforcing ways (Litan and Rivlin, 2001). Given this potential a recent OECD (2000) finding that indicates the European Union is lagging behind the United States (US) in terms of Internet penetration is important. That study shows, e.g., that in March 2000 there were 185 Internet hosts per 1,000 inhabitants in the US compared to 41 per 1,000 in the United Kingdom (UK) and 16 per 1,000 in France. Further, it is suggested that Internet access pricing structures may be a key factor in explaining penetration (Bourreau, 2001; Rappoport *et al*, 2002). A fairly natural question then for economists to consider is whether differential rates of Internet system growth is due to Internet access pricing structures or, more fundamentally, growth generated by direct network externalities after a critical system mass is achieved.

Direct network externalities occur when the utility of a consumer depends directly on the total number of compatible services (Gandal, 1995). Such direct network externalities have long been recognized in models explaining optimal telecommunications network size (Katz and Shapiro, 1986).[1] In this context subscribers' utility depends on the number of subscribers with compatible access (Economides, 1996). Rohlfs (1974) formulated the first model of the equilibrium number of telephone handsets in a population by focusing on individual constrained choice for telephone subscription incorporating parameters for consumer income and price. The equilibrium user set is the subscriber base resulting from the combined outcome of individual utility maximization programs. Multiple equilibriums may exist, with a small network making potential subscription relatively unattractive.

Economides and Himmelberg (1995) refine the notion of critical mass as the smallest size network that can be sustained in equilibrium. They argue that when the critical mass is substantial, market coverage will not be achieved — either the market does not exist or it is of insufficient coverage.[2] Accordingly, consumer willingness to adopt Internet service is an increasing function of network size (Shy, 2001). The existence of network externalities in a dynamic setting increases the speed at which market demand grows in the presence of a downward trend for industry marginal cost. Given the possible existence of a network externality for Internet connection (and e-commerce), estimates of the size of the network effect are critical for forecasting

[1] Rohlfs (1974), Littlechild (1975) and Oren and Smith (1981) analyse network externalities in the context of a monopoly telecommunications network.

[2] The field around the unstable critical mass point is "critical" in the sense that smaller fluctuations can have a large effect upon the continued development of diffusion (Schoder, 2000). Industries with network externalities typically exhibit a positive critical mass, that is, small networks are not observed at any price (Economides and Himmelberg 1995). The critical mass point can also be interpreted as the turning point between positive and negative returns to diffusion (Markus 1990).

demand and in network planning. Accordingly, a model is developed here to describe the global Internet market growth that provides a detailed analysis of the nature of the externality.

Bensaid and Lesne (1996) argue that most network externality models are developed in a static framework, with externalities viewed as either instantaneous or self-fulfilling. An Economides (1996) dynamic 'macro' approach is employed here to analyze the role network externalities have in explaining Internet system growth in a continuous-time setting. The 'macro' approach simply assumes network externalities exist and attempts to model their consequences.[3] Interaction between agents' (consumers' and firms') decisions is considered by a representative agent model in which sustained growth is the result of positive externalities from investment in network input *n*. Agents are linked through income flows and endogenous growth in the Internet network occurs through the inclusion of a network externality in the production argument in the firms' production function and also in the consumer's instantaneous utility function. The system is stochastic because the return to the representative consumer from non-network investment is uncertain.

The stochastic income specification leads to a stochastic inter-temporal optimization problem. The resultant solution provides an optimized network growth equation for estimation. The model is estimated on cross-country panel data to yield a direct measure of the network effect.

[3] The 'micro' approach is more concerned with the actual configuration of the network so as to better understand the origin of any externalities (Economides, 1996).

The paper is organized as follows. Section II specifies a model to examine Internet network growth that incorporates a network externality. In Section III data and variables used in estimation are presented and described. The empirical modeling strategy is explained in Section IV, and estimates of network externalities are reported. Concluding remarks and policy implications are provided in Section V.

II. A DYNAMIC MODEL OF INTERNET NETWORK GROWTH

Consider a decentralized economy that consists of a representative household and a representative firm that behaves competitively. The firm controls network and non-network input levels. A positive externality is associated with network investment through production activity. Internet network externalities can also arise through consumption. A representative consumer obtains utility from real total consumption and current network size. The consumer has the option not to consume all her income. Saving can occur through network investment. The consumer can, moreover, elect to relinquish ownership of part of the network in exchange for ownership of some other asset as a form of saving that provides a risky return.

Network Production Externalities

Let $F(v,n,n^*)$ denote the production function of a representative firm where v is either an aggregate non-network input or a vector of non-network inputs, e.g., labour and non-network capital. Let n^* represent a network externality generated through productive activity. This argument allows "endogenous growth" to occur in the network growth equation, viz., the production function exhibits decreasing returns in

n (from the perspective of the firm) and increasing returns when n is equated to $n*$ post-optimization. That is, during optimization $n*$ is treated by the firm as exogenous, and post-optimization $n*$ is equated to n when model equations are derived. Thus positive externalities arise from network capital and are a source of increasing returns in production. Let w represent an appropriate price of variable inputs. Illustration of the "optimizing out" process is provided for the case where v is treated as a variable input. Consider the specification for the production function:

$$F(v,n,n^*) = v^{\alpha} n^{1-\alpha} \left(1+n^*\right)^{\beta} \tag{1}$$

and the instantaneous variable profit function (conditional on network size, n):

$$\Pi(w,n,n^*) = \max_v \left\langle F(v,n,n^*) - wv \right\rangle . \tag{2}$$

The solution for optimal v, say $\hat{v}$, is:

$$\hat{v} = \alpha^{1/(1-\alpha)} w^{-1/(1-\alpha)} \left(1+n^*\right)^{\beta/(1-\alpha)} n \tag{3}$$

where the linearity of $\hat{v}$ in n follows from the linear homogeneity of the production function in (v,n).

Conditional on the *n*, optimized output can then be constructed (as a function of input prices) as:

$$\hat{F}\left(w,n,n^*\right)=\alpha^{\alpha/(1-\alpha)}w^{-\alpha/(1-\alpha)}\left(1+n^*\right)^{\beta/(1-\alpha)}n \tag{4}$$

and the linearity of optimized output in n, i.e., from the point of view of the firm's optimization, without internalizing the externality, is emphasized by writing:

$$\hat{F}(w,n,n^*)=R(w,n^*)\,n \tag{5}$$

where $R(w,n^*)$, the return per unit of network capital, is:

$$R(w,n^*)=\alpha^{\alpha/(1-\alpha)}w^{-\alpha/(1-\alpha)}\left(1+n^*\right)^{\beta/(1-\alpha)}. \tag{6}$$

Since $\partial R(w,n^*)/\partial n^*>0,$ the production network externality manifests itself as a positive dependence of the return per unit of network capital (the "interest rate" in this stylized model) on network size.

Network Consumption Externalities

Internet network externalities can also arise through consumption. Let $U(c,n^*)$ denote the instantaneous utility function of a representative consumer where c is real total consumption (so $U(c,\bullet)$ can be treated as an indirect utility function) and n^* is the current network size (which is outside the control of the consumer).

Temporarily setting aside the network effect, specify $U(c,\bullet)$ in the iso-elastic form:

$$U(c,\bullet)=c^{\gamma}. \tag{7}$$

The inter-temporal elasticity of substitution ($IES = -\partial \ln c / \partial \ln U_c$) for (7) is:

$$IES = 1/(1-\gamma)\,, \tag{8}$$

where $-\infty < \gamma < 1$. The *IES* indicates the willingness of the consumer to forego current consumption in favour of current saving and greater discounted future utility. A natural way to introduce network consumption externalities into the framework is to model them as influencing the *IES*. A possible specification is:

$$IES = \theta_1 \left[\frac{1}{1+n^*} \right] + \theta_2 \left[\frac{n^*}{1+n^*} \right]. \tag{9}$$

In (9) the *IES* ranges in value from θ_1 when there is no network rollout $(n^* = 0)$ and asymptotes to θ_2 as the network expands indefinitely $(n^* \to \infty)$. The *IES* is increasing in n^* if $\theta_2 > \theta_1$. Accordingly, the utility function incorporating network externality effects may be written as a function of network size $G(n^*)$. That is,

$$U(c, n^*) = c^{G(n^*)} \tag{10}$$

where since $IES = 1/\left[1 - G(n^*)\right]$ or $G(n^*) = 1 - 1/IES$, and with the IES given by (8), $G(n^*)$ is specified as:

$$G(n^*) = 1 - \frac{1}{\theta_1 \left[\frac{1}{1+n^*} \right] + \theta_2 \left[\frac{n^*}{1+n^*} \right]}. \tag{11}$$

Income Flows

In this model income is derived from productive capacity and a stochastic return to equity investment obtained by selling x of the network n, thereby foregoing a sure rate of return $R(w,n^*)\,x\,dt$ and in return receiving the risky return $x\,dq/q$. Here the risky asset is assumed to pay no dividend and to receive return from capital gain only. The resulting flow of income from production and investment sources is:

$$dy = R(w,n^*)\,n\,dt + \left[dq/q - R(w,n^*)\,dt\right]x \tag{12}$$

where the price of the risky asset, q, is modeled as following a geometric Brownian motion with drift μ_q and volatility σ_q:

$$dq = \mu_q\,q\,dt + \sigma_q\,q\,dz_q \tag{13}$$

and dz_q is Brownian motion, with the properties $E\left(dz_q\right) = 0$, $E\left(dz_q\right)^2 = dt$.[4]

An alternative to consumption is saving (personal investment) through the medium of the only durable good contained in the model, hence by purchase of access to the network. Saving by the representative consumer can also occur through foregoing network assets in exchange for risky return. The network access price p converts the

[4] In a more general formulation, if the equity investment is in "new economy" stocks, then the drift and volatility might be modeled as functions of the network size, leading potentially to another source of network externalities.

value of the network extension into units of the consumption good. Consequently, network expansion is stochastic and the demand side of the income identity is:

$$dy = c\,dt + p\,dn\,. \tag{14}$$

Optimization Model

For the stochastic income specification (12)-(14), the representative consumer's inter-temporal optimization problem is:

$$J(n_0, p_0, w_0) = \max_{\{c(t),x(t)\}} E_0 \int_0^{\infty} e^{-\delta t} U(c(t), n^*(t))dt \tag{15}$$

subject to

$$dn = \left[\frac{R(w,n^*)n - c}{p}\right]dt + \left[\frac{dq/q - R(w,n^*)dt}{p}\right]x \tag{16}$$

$$dq = \mu_q q\,dt + \sigma_q q\,dz_q \tag{17}$$

$$dp = \mu_p pdt + \sigma_p pdz_p \tag{18}$$

$$dw = \mu_w wdt + \sigma_w wdz_w \tag{19}$$

$$n^*(t) = n(t)\,, t \in [0, \infty) \tag{20}$$

$$n(0) = n_0\,,\quad p(0) = p_0\,,\quad w(0) = w_0 \tag{21}$$

Optimized Network Growth Equation

Combining (16) and (17) the network growth equation can be characterized as a diffusion of the form:

$$dn = \left\{ \frac{R(w,n^*)n + \left[\mu_q - R(w,n^*)\right]x - c}{p} \right\} dt + \frac{\sigma_q x}{p} dz_q . \tag{22}$$

It is clear from the time-autonomous nature of (15) that solution for c and x may be obtained in feedback or synthesized form, expressing the controls as a function of the current values of the states n, p and w. To describe the solution, it is useful to define some simplifying latent variables (interpretable as the interest rate and the *IES*, respectively):

$$r = R(w,n^*) \tag{23}$$

$$h = 1/\left[1 - G(n^*)\right] \tag{24}$$

and to note that $n = n^*$ in the optimized model.[5] In Cooper *et al* (1995) it is shown that optimal c may be written as:

$$\hat{c} = \left\{ h\delta + [1-h]\left[r + \tfrac{1}{2} h\left(\mu_q - r\right)^2 / \sigma_q^{\,2} \right] \right\} n \tag{25}$$

[5] Since the externality is irrelevant to the private optimiser, the problem is formally equivalent to a stochastic inter-temporal optimisation of the type described by Cooper *et al* (1995).

and optimal x may be written as:

$$\hat{x} = h\left[\frac{\mu_q - r}{\sigma_q{}^2}\right]n\,. \tag{26}$$

Utilizing the synthesized solutions (25) and (26), optimal network diffusion is therefore:

$$dn = h\left\{\frac{r - \delta + \frac{1}{2}[h+1]\left(\mu_q - r\right)^2 / \sigma_q{}^2}{p}\right\}n\,dt + h\left\{\frac{\mu_q - r}{\sigma_q p}\right\}n\,dz_q \tag{27}$$

where, in view of the specifications of technology and preferences, and setting $n = n^*$,

$$r = \alpha^{\alpha/(1-\alpha)} w^{-\alpha/(1-\alpha)} \left[1+n\right]^{\beta/(1-\alpha)} \tag{28}$$

and

$$h = \theta_1\left[\frac{1}{1+n}\right] + \theta_2\left[\frac{n}{1+n}\right]. \tag{29}$$

III. DATA AND VARIABLES

Equation (27), after substitution of (28) and (29), is estimated on a sample of 23 OECD countries.[6] Annual data from 1995 to 2000 are collected for CPI (Consumer Price Index), exchange rates, GDP (Gross Domestic Product), Internet access price, Internet hosts and wages. CPI, GDP and Internet host numbers (HOST) are obtained from International Telecommunication Union (ITU) *World Telecommunication Development Report*.[7] Internet access price data (PRICE) are sourced from *OECD Communications Outlook* for 1997, 1999 and 2001. PRICE is the price of Internet access for 20 hours per month peak rate in US dollars (USD) purchasing power parity. The price of Internet access is comprised of the timed public switched telephone network charge and monthly Internet service provider fee. Published PRICE data for 1996 is converted from USD to USD purchasing power parity (PPP). PRICE data for 1997 is not available and is interpolated.[8] Unpublished price data for 1999 is obtained directly from the OECD. PRICE is deflated using an adjusted CPI index. The CPI (1995 = 1) is adjusted to maintain currency relativities by multiplying the CPI index in each year by the 1996 USD PPP. The CPI is then converted into USD by dividing the country adjusted CPI by the nominal exchange rate. New hosts (ΔHOST = $HOST_t$

[6] The 23 countries are comprised of: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and the US. Mexico and Turkey are not included as they are outliers. Czech Republic, Hungary, Poland and South Korea are excluded because of insufficient Internet access price data.

[7] Complete GDP data are not available for Ireland (2000) and New Zealand (1999, 2000) in the ITU database and are obtained directly from the Central Statistics Office (Ireland) and Statistics New Zealand.

[8] A geometric procedure based on the rule $PRICE_{1997} = PRICE_{1996} \times \left(\frac{PRICE_{1998}}{PRICE_{1996}}\right)^{\frac{1}{2}}$ is used to interpolate the PRICE series.

– $HOST_{t-1}$) are obtained by first-differencing the HOST series. WAGE is the proportion of Compensation of Employees (OECD code: WSSS) in nominal GDP.[9]

Mean, standard deviation, minimum and maximum values for HOST, ΔHOST, PRICE and WAGE are reported in Table I. Host numbers (HOST) range in value from less than four thousand (Luxembourg) to in excess of 80 million (US). The mean addition to the HOST count (ΔHOST), across both countries and time, is almost 800,000. Eleven countries have recorded declines in host numbers with the largest decline in France (2000).[10] PRICE, the listed price of dominant ISP and PSTN carriers, ranges in value from USD19.86 (US) to USD291.43 (Mexico). Average WAGE is 48% of GDP and reflects considerable variation across the sample ranging from 26% (Turkey) to 61% (Switzerland).

TABLE I. SUMMARY STATISTICS 1996-2000

Variable	Mean	Standard Deviation	Minimum	Maximum
Complete sample				
HOSTS	2,043,942.03	9,130,292.01	3,518.00	80,566,944.00
ΔHOSTS	737,982.50	3,397,557.20	-110,664.00	27,390,988.00
PRICE	53.05	33.73	18.96	291.43
WAGE	0.48	0.08	0.26	0.61
Sample with Mexico and Turkey excluded				
HOSTS	2,209,516.43	9,504,014.16	3,518.00	80,566,944.00
ΔHOSTS	796,852.70	3,537,170.96	–110,664.00	27,390,988.00
PRICE	48.41	20.36	18.96	135.69
WAGE	0.50	0.06	0.32	0.61

Note: HOST is host numbers. ΔHOST = $HOST_t$ – $HOST_{t-1}$. PRICE is the real price of Internet access in USD purchasing power parity.

Sample scatter plots of PRICE and ΔHOST, and WAGE and ΔHOST for the period 1996 through 2000 are shown in Figure I through Figure IV below. Figure I show an

[9] Compensation of Employees is obtained directly from the OECD.
[10] The countries with declines in new hosts are: Belgium, Denmark, Finland, France, Italy, New Zealand, Portugal, Spain, Switzerland, Turkey and the United Kingdom.

apparent negative relationship between PRICE and ΔHOST (sample pair-wise correlation of -0.1462). Apart from Turkey, ΔHOST observations are clustered but spread evenly around mean PRICE. The extreme right-hand observations are for the US. Figure II excludes the US, showing that the relationship between PRICE and ΔHOST is maintained.

FIGURE I. OECD PRICE AND ΔHOST, 1996-2000

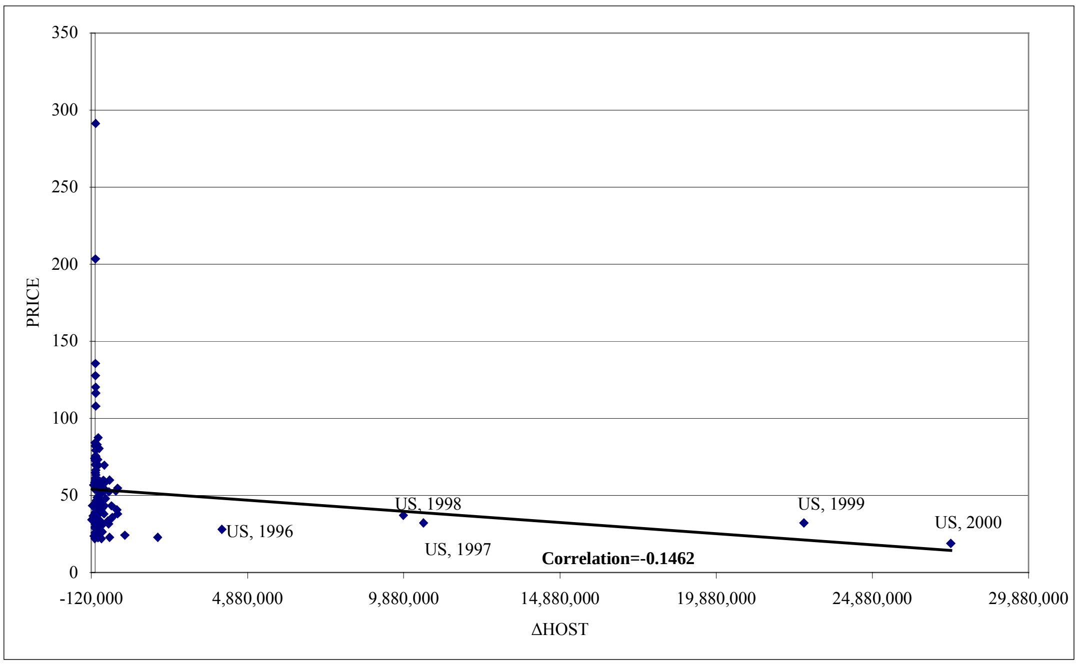

FIGURE II. OECD PRICE AND ΔHOST (EXCLUDING THE US), 1996-2000

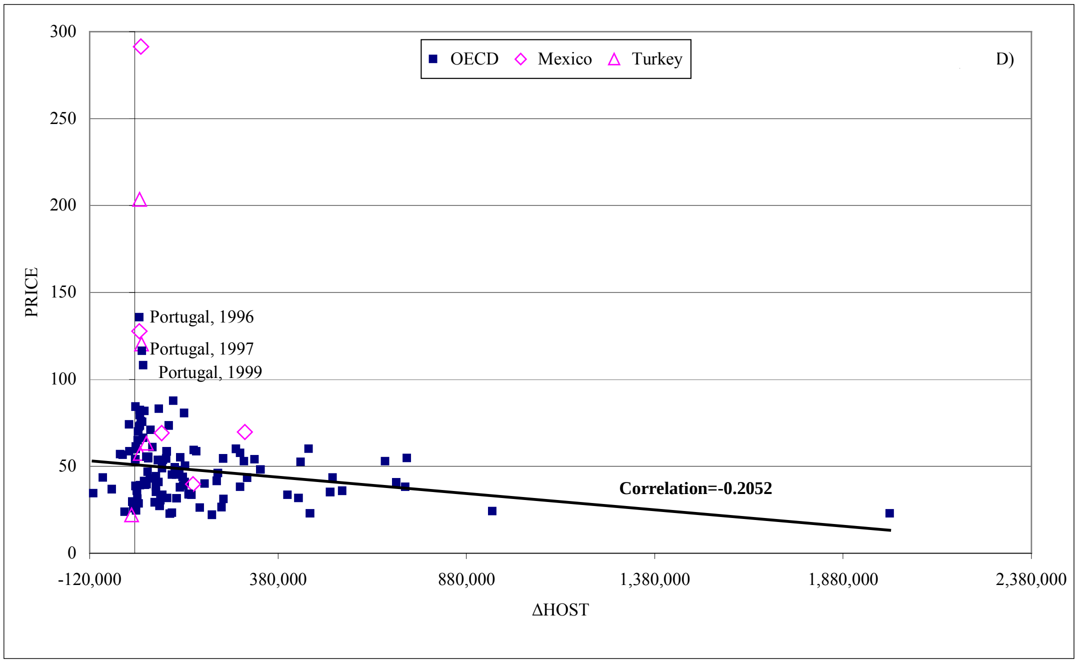

FIGURE III. OECD UNIT WAGES AND ΔHOST, 1996-2000

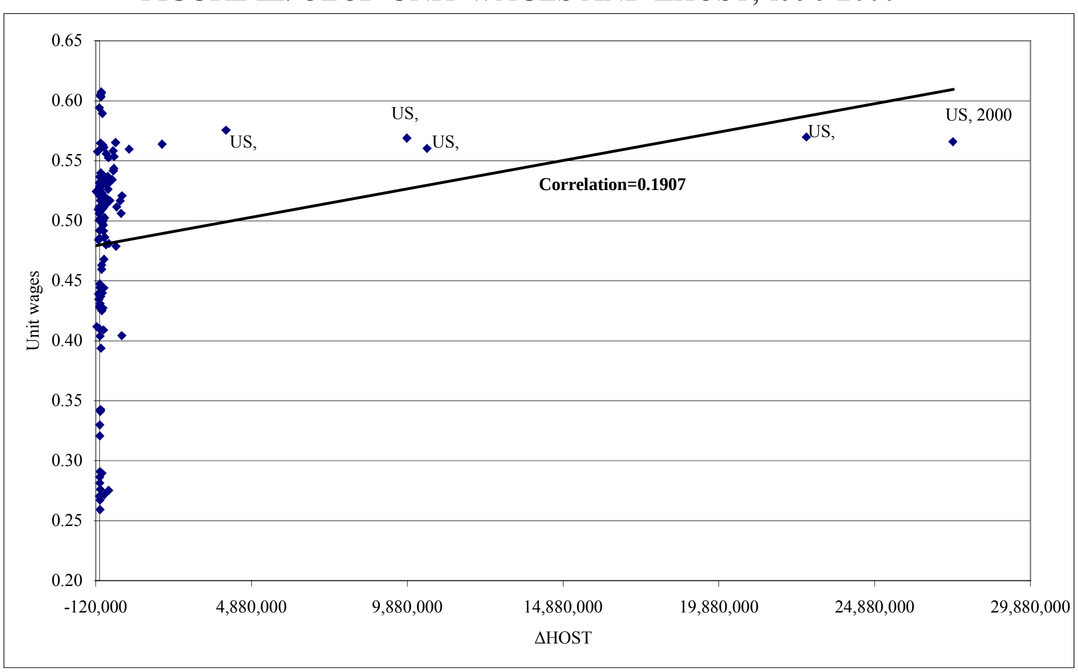

FIGURE IV. OECD UNIT WAGES AND ΔHOST (EXCLUDING US), 1996-2000

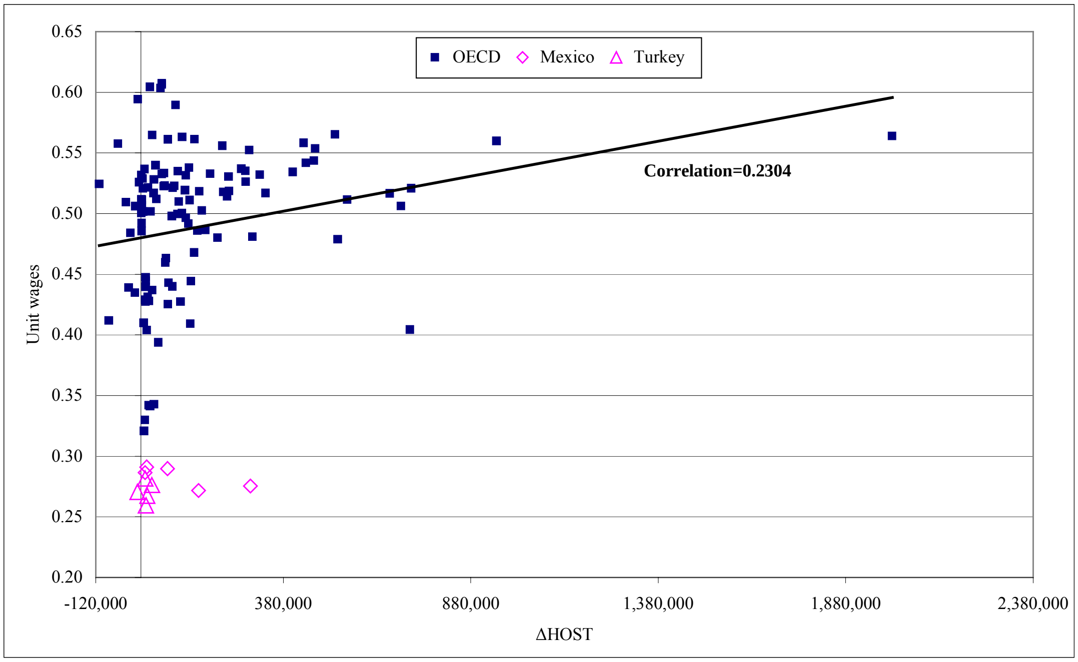

Figure III displays a positive relationship between WAGE and ΔHOST (sample pair-wise correlation of 0.1907). Exclusion of the US results in the correlation increasing to 0.2304.

IV. MODEL ESTIMATION

Functional Form Specification and Economic Theory

The network growth equation was derived in Section II in continuous time as (27) to (29). Converting to discrete time, let $dt = 1$, $dn = n_t - n_{t-1} = \Delta n_t$ and $dz_q = \varepsilon_q \sim N(0,1)$. The estimating form becomes:

$$\frac{\Delta n_t}{n_{t-1}} = \left\{\theta_1\left[\frac{1}{1+n_{t-1}}\right]+\theta_2\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\}\frac{\alpha^{\alpha/(1-\alpha)}w_t^{-\alpha/(1-\alpha)}\left[1+n_{t-1}\right]^{\beta/(1-\alpha)}-\delta}{p_t}$$
$$+\tfrac{1}{2}\left\{\theta_1\left[\frac{1}{1+n_{t-1}}\right]+\theta_2\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\}\left\{(1+\theta_1)\left[\frac{1}{1+n_{t-1}}\right]+(1+\theta_2)\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\} \quad (30)$$
$$\times\frac{\left(\mu_q-\alpha^{\alpha/(1-\alpha)}w_t^{-\alpha/(1-\alpha)}\left[1+n_{t-1}\right]^{\beta/(1-\alpha)}\right)^2}{p_t\sigma_q^{\ 2}} + \varepsilon_{n,t}$$

with the error term:

$$\varepsilon_{n,t} = \left\{\theta_1\left[\frac{1}{1+n_{t-1}}\right]+\theta_2\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\}\left[\frac{\mu_q-\alpha^{\alpha/(1-\alpha)}w_t^{-\alpha/(1-\alpha)}\left[1+n_{t-1}\right]^{\beta/(1-\alpha)}}{p_t\sigma_q}\right]\varepsilon_{q,t}. \quad (31)$$

It is useful to identify the following components of (30): the inter-temporal elasticity of substitution,

$$IES = h = \left\{\theta_1\left[\frac{1}{1+n_{t-1}}\right]+\theta_2\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\} \quad (32)$$

the “interest rate” (rate of return to the network as a productive resource), r

$$r = \alpha^{\alpha/(1-\alpha)}w_t^{-\alpha/(1-\alpha)}\left[1+n_{t-1}\right]^{\beta/(1-\alpha)} \quad (33)$$

and the relative risk premium (RRP), which is defined as the normalized equity premium, $(\mu_q - r)/\sigma$ relative to the network access price, p

$$RRP = \left[\frac{\mu_q - r}{\sigma_q}\right]/\,p\,. \quad (34)$$

The potential heteroscedasticity implied by (31) is seen as deriving from $IES \times RRP$. Rather than account for this through mechanical adjustment procedures, variable parameter specifications are formulated for components of the IES and RRP to allow offsetting effects to reduce the overall extent of heteroscedasticity. Country-specific and time-specific adjustment factors are added to (30) to provide:

$$\begin{aligned}\frac{\Delta n_t}{n_{t-1}} &= \left\{\theta_{1,t}\left[\frac{1}{1+n_{t-1}}\right]+\theta_2\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\}\frac{A_c\,T_t\,w_t^{-\alpha/(1-\alpha)}\left[1+n_{t-1}\right]^{\beta/(1-\alpha)}-\delta}{p_t} \\ &\quad+\tfrac{1}{2}\left\{\theta_{1,t}\left[\frac{1}{1+n_{t-1}}\right]+\theta_2\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\}\left\{\left(1+\theta_{1,t}\right)\left[\frac{1}{1+n_{t-1}}\right]+\left(1+\theta_2\right)\left[\frac{n_{t-1}}{1+n_{t-1}}\right]\right\} \\ &\quad\times\frac{\left(\mu_t - A_c\,T_t\,w_t^{-\alpha/(1-\alpha)}\left[1+n_{t-1}\right]^{\beta/(1-\alpha)}\right)^2}{p_t\sigma_t^{\,2}} + \varepsilon_t\end{aligned} \tag{35}$$

where it is assumed $\varepsilon_t \sim IID\ N(0,\sigma_\varepsilon^{\,2})$.

Other adjustments to (30) contained in (35) include subsuming the constant parameter function $\alpha^{\alpha/(1-\alpha)}$ into the production function "intercept" term A. The adjusted intercept is specified as the product of the terms:

$$A_c = \alpha_a + \alpha_0 e^{\sum_{j=1}^{23} c_j d_j} \tag{36}$$

and

$$T_t = \tau_a + e^{\tau_b(t-1)+\tau_c(t-1)^2} \Big/ \left(1+\tau_0 e^{\tau_b(t-1)+\tau_c(t-1)^2}\right) \tag{37}$$

where the c_j and d_j are country-specific parameters and indicator variables ($j = 1,...,23$), respectively. After a grid search, α_a and α_0 are pre-set at $\alpha_a = 0.1, \alpha_0 = 0.01$, and τ_a and τ_0 are pre-set at $\tau_a = 0.01, \tau_0 = 19$. The remaining parameters, c_j in the case of the country scale factor A_c and τ_b and τ_c in the case of the time scale factor T_t, are freely estimated in the non-linear maximum likelihood estimation routine.

Further, θ_1, μ_q and σ_q are specified as time varying, and are denoted by $\theta_{1,t}, \mu_t$ and σ_t, respectively. Thus:

$$\theta_{1,t} = \theta_0 + \theta_c \left[\frac{n_{t-1}^{c} - n_{t-1}^{US}}{n_{t-1}^{US}} \right] \tag{38}$$

$$\mu_t = \mu_a + e^{\mu_b (t-1) + \mu_c (t-1)^2} / \left(1 + \mu_0 e^{\mu_b (t-1) + \mu_c (t-1)^2} \right) \tag{39}$$

$$\sigma_t = \sigma_a + e^{\sigma_b (t-1) + \sigma_c (t-1)^2} / \left(1 + \sigma_0 e^{\sigma_b (t-1) + \sigma_c (t-1)^2} \right). \tag{40}$$

Following a grid search, the following parameter settings are imposed, $\mu_a = 0.01, \mu_0 = 4, \sigma_a = 0.05$, and $\sigma_0 = 29$. The remaining parameters, θ_0, θ_c, μ_b, μ_c, σ_b and σ_c, are freely estimated in the maximum likelihood routine.

Because of the form of the non-linearity in (35), free estimation of the time preference rate δ is problematic. Accordingly, this parameter is set at $\delta = 0.02$ (after a grid search). Additionally, experimentation with different forms for construction of the network externality variable (the raw numbers of Internet hosts versus construction of an index indicating cumulative growth from the beginning of the sample period) and with different measures of the externality (world versus country network size) was undertaken with a view to improving estimation prospects given the non-linear specification. This experimentation led to a preference for the index approach and to different preferred network externality measures for the consumption as distinct from the production externalities.

Bringing the above considerations together, the preferred specification is:

$$\frac{\Delta n_t}{n_{t-1}} = IES_t \frac{r_t - 0.02}{p_t} + \tfrac{1}{2} IES_t \left[1 + IES_t\right] RRP_t \ + \ \varepsilon_t \qquad (41)$$

where IES_t, RRP_t and r_t are shorthand respectively for:

$$IES_t = \left\{\theta_0 + \theta_c \left[\frac{n^c_{t-1} - n^{US}_{t-1}}{n^{US}_{t-1}}\right]\right\}\left[\frac{1}{1+0.5 n^W_{t-1}}\right] + \theta_2 \left[\frac{0.5 n^W_{t-1}}{1+0.5 n^W_{t-1}}\right] \qquad (42)$$

$$RRP_t = \frac{\left(0.01 + \dfrac{e^{\mu_b (t-1) + \mu_c (t-1)^2}}{1 + 4 e^{\mu_b (t-1) + \mu_c (t-1)^2}} - r_t\right)^2}{p_t \left(0.05 + \dfrac{e^{\sigma_b (t-1) + \sigma_c (t-1)^2}}{1 + 29 e^{\sigma_b (t-1) + \sigma_c (t-1)^2}}\right)^2} \qquad (43)$$

$$r_t = \left[0.1 + 0.01 e^{\sum_{j=1}^{23} c_j d_j} \right] \left[0.01 + \frac{e^{\tau_b (t-1) + \tau_c (t-1)^2}}{1 + 19 e^{\tau_b (t-1) + \tau_c (t-1)^2}} \right] w_t^{-\alpha/(1-\alpha)} \times \left[1 + n_{t-1}^{W} d_{US} \right]^{\beta_W /(1-\alpha)} \left[1 + n_{t-1}^{c} (1 - d_{US}) \right]^{\beta_C /(1-\alpha)} \tag{44}$$

and the network measures are indices constructed from Internet host numbers by:

$$n_{t-1}^{c} = \frac{HOST_{t-1}^{c} - HOST_0^{c}}{HOST_0^{c}}, \ t = 1,...,5, \ c = 1,...,23, \text{ with 0 denoting year 1995}.$$

Before proceeding, some interpretation for the variable parameter specifications is provided. By construction, $n_{t-1}^{c} = 0$ for $t = 1$. At $t = 1$ the interest rate applicable to holding the network stock is:

$$r_1 = \left[0.1 + 0.01 e^{\sum_{j=1}^{23} c_j d_j} \right] 0.06 w_1^{-\alpha/(1-\alpha)}$$

and variations in the interest rate across countries in the initial period reflect different real wage conditions and differences in initial technology and network externality effects, which are captured by the c_j.

In this specification, the technology parameter T_t takes the value $T_1 = 0.06$ for all countries at time $t = 1$, 1996, hence acting as a normalizing constant at that time. The specification:

$$T_t = 0.01 + \frac{e^{\tau_b (t-1) + \tau_c (t-1)^2}}{1 + 19 e^{\tau_b (t-1) + \tau_c (t-1)^2}}$$

allows for non-monotonic behaviour of network stock efficiency in production, with common country behaviour over the period determined by the freely estimated parameters τ_b and τ_c. When $\tau_b(t-1) + \tau_c(t-1)^2$ takes a large negative value, T_t will tend to 0.01, the imposed lower bound on T_t. In this specification, T_t can rise above its value at T_1, but not by very much. The imposed upper bound on T_t is approximately 0.0626. This tight upper bound is imposed by the high value of the scaling constant $\tau_0 = 19$ (imposed to improve economic meaningfulness after a grid search). In estimation the parameters τ_b and τ_c take values that imply an initial drop in T_t, so the upper bound is not binding.

Based on similar considerations, the remaining constrained non-linear variable parameter functions are described below. The country-specific effect is:

$$A_c = 0.1 + 0.01 e^{\sum_{j=1}^{23} c_j d_j}$$

and has a lower bound of 0.1 and no upper bound. In the estimation, a result of $c_9 = -91.381$ implies the lower bound is binding for Greece. Other countries are not affected by this constraint. A typical estimated value of $c_j = 3$ produces a country A_c parameter of $A_c = 0.3$ approximately.

The expected rate of return on the risky asset is modeled as:

$$\mu_t = 0.01 + \frac{e^{\mu_b (t-1)+\mu_c (t-1)^2}}{1+4e^{\mu_b (t-1)+\mu_c (t-1)^2}}.$$

This forces $\mu_1 = 0.21$ and allows μ_t to vary, possibly non-monotonically, from a minimum of 0.01 to a maximum of 0.26, with values dependent on the freely estimated parameters μ_b and μ_c. In estimation μ_t initially fell and then rose but neither the minimum nor maximum constraint is binding.

The volatility of the risky asset is modeled as:

$$\sigma_t = 0.05 + \frac{e^{\sigma_b (t-1)+\sigma_c (t-1)^2}}{1+29e^{\sigma_b (t-1)+\sigma_c (t-1)^2}}.$$

This specification gives a lower bound of 0.05 for σ_t. It also enforces an initial value of $\sigma_1 = 0.083$ and an upper bound of approximately 0.0845, so that σ_t is constrained to begin near its upper bound. In estimation, σ_t fell to the lower bound by the latter part of the sample.

The main stylized fact these variable parameter specifications are meant to capture is the fall in the expected rate of return on the risky asset in the mid-sample period, making some allowance for the Asian financial crisis and world financial conditions more generally. Additionally, from an econometric point of view, the accompanying but lesser fall in volatility leads to a reduced, though still substantial, fall in the RRP that in part ameliorates the effect of the rise in the IES on theory-induced heteroscedasticity in the model.

Maximum Likelihood Estimates

Non-linear maximum likelihood estimation of (41) is performed using SHAZAM Version 8 (White, 1997). Parameter estimates and asymptotic t-statistics are presented in Table II. The key results concern parameters associated with network externalities in consumption and production. Concentrating first on consumption externalities, these are measured through the parameters θ_0, θ_c and θ_2 that make up the IES. Although the country specific-effect θ_C is estimated as quite small at –0.619, and shows up as insignificant according to the asymptotic t-statistic, a likelihood ratio (LR) test rejects the restriction that $\theta_C = 0$ (LR=24.960, critical $\chi_1^2(.01) = 6.63$). Therefore, the results with θ_C freely estimated are reported. From an economic perspective, however, the country-specific effect is undoubtedly minor. Treating the insignificant country-specific effect θ_C as zero for purposes of discussion, the time-varying specification for $\theta_{1,t}$ reduces to θ_0. The relatively more significant (recognizing that the t-statistics are only valid asymptotically) estimates of θ_0 and θ_2 imply that the IES ranges from 3.321 in 1996 and is projected to asymptote towards the estimate of θ_2, i.e., 16.657 as world network grows indefinitely large. It is essentially the difference between the 1996 value of 3.321 and the asymptotic value of 16.657 for the IES that indicates the importance of the network externality in consumption, since the nature of the IES specification is that if there were no effect of the network on utility then the IES would be constant.[11] Under the joint null hypothesis $\theta_C = 0, \theta_0 = \theta_2$, there would be no network externality in consumption. This joint null hypothesis is rejected by the data (LR=51.756, critical $\chi_2^2(.01) = 9.21$).

TABLE II. ESTIMATION RESULTS

Parameter	Estimate	t-Ratio
θ_0	3.321	3.608
θ_C	–0.649	–0.699
θ_2	16.657	2.675
α	0.584	10.807
β_w	0.334	2.797
β_c	0.461	3.185
Australia	4.111	19.468
Austria	3.278	37.295
Belgium	1.987	5.427
Canada	3.890	26.161
Denmark	3.153	24.884
Finland	4.423	16.316
France	2.918	18.213
Germany	4.023	27.406
Greece	–91.381	–2.756
Iceland	4.217	25.194
Ireland	2.725	14.496
Italy	2.837	17.357
Japan	2.932	16.488
Luxembourg	3.278	26.042
Netherlands	3.150	28.019
NZ	3.159	17.232
Norway	3.373	21.993
Portugal	2.683	15.568
Spain	2.463	11.018
Sweden	4.253	28.521
Switzerland	4.310	30.717
UK	3.965	30.520
US	3.809	8.639
τ_B	–6.169	–7.179
τ_C	1.258	5.771
μ_B	–2.215	–9.306
μ_C	0.464	6.449
σ_B	2.324	0.084
σ_C	–2.294	–0.171
R^2 statistic	0.716	
L	18.489	

Note. R^2 is the squared correlation coefficient between observed and predicted values. L is the log of the likelihood. t-ratio is asymptotic.

[11] The IES measures the flexibility available to consumers to re-configure their consumption/savings choices as perceived economic conditions change. Specifically, the IES measures the elasticity of consumption behaviour with respect to the co-state variable in the model, a theoretical construct which measures the marginal utility of changes in wealth.

Turning to the evidence concerning production externalities, the crucial parameters are β_w for externalities related to the size of the world network estimated at 0.334 and β_c for externalities related to the size of the country network estimated at 0.461. The world stock network externality is related to US hosts but not other country hosts, while the reverse is true for the country network size externality, which is relevant for countries other than the US. At this point the significance of these effects is simply noted. A likelihood ratio test of the joint null hypothesis $\beta_w = 0,\ \beta_c = 0$ decisively rejects the null (LR=97.688, critical $\chi_2^2(.01) = 9.21$). In the context of the overall production function, and given the specification of internal linear homogeneity in these functions, the results imply effective increasing returns to scale due to the externality of 1.334 for the US (with the world network size providing the externality) and 1.461 for other countries (with the size of the country-specific stock providing the externality).

An ancillary production function parameter is α. Estimated at 0.584, this indicates the variable factor input share of output income is 58%. Remaining parameter estimates control for country-specific effects in technology, the extent of externalities prior to 1996, for variation in the normalized risk premium and the returns to Internet investment over time. Generally, these results indicate the importance of allowing for these variations in the pooled data set.

Table III reports variable parameter estimates and other relevant functions that vary across countries or time. Column (iii) and Column (iv), labeled A_C and T respectively, provide estimates of the country-specific component and time-specific components which together define the multiplicative scale factor for the interest rate, viz., $A_C T_t$ in the expression for r_t :

$$r_t = A_C\, T_t\, w_t^{-\alpha/(1-\alpha)} \left[1 + n_{t-1}^{W} d_{USA}\right]^{\beta_W/(1-\alpha)} \left[1 + n_{t-1}^{c}(1 - d_{USA})\right]^{\beta_C/(1-\alpha)} . \qquad (45)$$

The interest rate, constructed according to (45), is given in Column (vii) of Table III. Column (v) and Column (vi) report the remaining variable parameter components of the normalized risk premium $(\mu - r)/\sigma$, viz., σ and μ. A comparison of Column (vi) and Column (vii) shows that the risk premium is positive over the majority of countries and time periods, with negative values reported for seven countries only, and all in the final time period. Preliminary grid searches for economically sensible values of parameters controlling upper and lower limits on the allowable variation in estimates of T_t, μ_t and σ_t and a lower limit for A_C are based on minimizing the number of violations of positivity of the risk premium. Given these pre-set values, maximum likelihood estimation proceeded on the basis of generation of a minimal number of these economically problematic results. Further, elimination of these few negative risk premium results, while desirable, would probably require more complex variable parameter specifications over time and countries than can sensibly be supported by the data set.

TABLE III. VARIABLE PARAMETER ESTIMATES

(i) Country	(ii) Year	(iii) A_C	(iv) T	(v) σ	(vi) μ	(vii) R	(viii) IES	(ix) γ
Australia	1996	0.710	0.060	0.083	0.210	0.119	3.938	0.746
Australia	1997	0.710	0.016	0.083	0.112	0.057	7.280	0.863
Australia	1998	0.710	0.011	0.058	0.068	0.048	10.571	0.905
Australia	1999	0.710	0.011	0.050	0.073	0.060	12.112	0.917
Australia	2000	0.710	0.019	0.050	0.132	0.152	13.700	0.927
Austria	1996	0.365	0.060	0.083	0.210	0.054	3.965	0.748
Austria	1997	0.365	0.016	0.083	0.112	0.026	7.301	0.863
Austria	1998	0.365	0.011	0.058	0.068	0.021	10.579	0.905
Austria	1999	0.365	0.011	0.050	0.073	0.036	12.117	0.917
Austria	2000	0.365	0.019	0.050	0.132	0.101	13.703	0.927
Belgium	1996	0.173	0.060	0.083	0.210	0.026	3.967	0.748
Belgium	1997	0.173	0.016	0.083	0.112	0.017	7.302	0.863
Belgium	1998	0.173	0.011	0.058	0.068	0.019	10.579	0.905
Belgium	1999	0.173	0.011	0.050	0.073	0.040	12.117	0.917
Belgium	2000	0.173	0.019	0.050	0.132	0.121	13.702	0.927
Canada	1996	0.589	0.060	0.083	0.210	0.090	3.931	0.746
Canada	1997	0.589	0.016	0.083	0.112	0.042	7.276	0.863
Canada	1998	0.589	0.011	0.058	0.068	0.038	10.568	0.905
Canada	1999	0.589	0.011	0.050	0.073	0.055	12.110	0.917
Canada	2000	0.589	0.019	0.050	0.132	0.152	13.699	0.927
Denmark	1996	0.334	0.060	0.083	0.210	0.049	3.965	0.748
Denmark	1997	0.334	0.016	0.083	0.112	0.030	7.300	0.863
Denmark	1998	0.334	0.011	0.058	0.068	0.032	10.578	0.905
Denmark	1999	0.334	0.011	0.050	0.073	0.061	12.116	0.917
Denmark	2000	0.334	0.019	0.050	0.132	0.127	13.702	0.927
Finland	1996	0.933	0.060	0.083	0.210	0.148	3.948	0.747
Finland	1997	0.933	0.016	0.083	0.112	0.064	7.290	0.863
Finland	1998	0.933	0.011	0.058	0.068	0.068	10.574	0.905
Finland	1999	0.933	0.011	0.050	0.073	0.064	12.115	0.917
Finland	2000	0.933	0.019	0.050	0.132	0.120	13.702	0.927
France	1996	0.285	0.060	0.083	0.210	0.043	3.954	0.747
France	1997	0.285	0.016	0.083	0.112	0.019	7.294	0.863
France	1998	0.285	0.011	0.058	0.068	0.020	10.576	0.905
France	1999	0.285	0.011	0.050	0.073	0.030	12.114	0.917
France	2000	0.285	0.019	0.050	0.132	0.136	13.700	0.927
Germany	1996	0.659	0.060	0.083	0.210	0.090	3.920	0.745
Germany	1997	0.659	0.016	0.083	0.112	0.039	7.272	0.862
Germany	1998	0.659	0.011	0.058	0.068	0.045	10.564	0.905
Germany	1999	0.659	0.011	0.050	0.073	0.059	12.107	0.917
Germany	2000	0.659	0.019	0.050	0.132	0.118	13.699	0.927
Greece	1996	0.100	0.060	0.083	0.210	0.030	3.970	0.748
Greece	1997	0.100	0.016	0.083	0.112	0.018	7.304	0.863
Greece	1998	0.100	0.011	0.058	0.068	0.020	10.581	0.905
Greece	1999	0.100	0.011	0.050	0.073	0.038	12.118	0.917
Greece	2000	0.100	0.019	0.050	0.132	0.105	13.703	0.927
Iceland	1996	0.778	0.060	0.083	0.210	0.120	3.970	0.748
Iceland	1997	0.778	0.016	0.083	0.112	0.049	7.304	0.863
Iceland	1998	0.778	0.011	0.058	0.068	0.050	10.581	0.905
Iceland	1999	0.778	0.011	0.050	0.073	0.069	12.118	0.917
Iceland	2000	0.778	0.019	0.050	0.132	0.145	13.703	0.927
Ireland	1996	0.253	0.060	0.083	0.210	0.047	3.969	0.748
Ireland	1997	0.253	0.016	0.083	0.112	0.030	7.304	0.863
Ireland	1998	0.253	0.011	0.058	0.068	0.032	10.580	0.905
Ireland	1999	0.253	0.011	0.050	0.073	0.046	12.118	0.917
Ireland	2000	0.253	0.019	0.050	0.132	0.099	13.703	0.927

(i) Country	(ii) Year	(iii) A_C	(iv) T	(v) σ	(vi) μ	(vii) R	(viii) IES	(ix) γ
Italy	1996	0.271	0.060	0.083	0.210	0.054	3.963	0.748
Italy	1997	0.271	0.016	0.083	0.112	0.031	7.298	0.863
Italy	1998	0.271	0.011	0.058	0.068	0.039	10.577	0.905
Italy	1999	0.271	0.011	0.050	0.073	0.062	12.115	0.917
Italy	2000	0.271	0.019	0.050	0.132	0.084	13.703	0.927
Japan	1996	0.288	0.060	0.083	0.210	0.040	3.942	0.746
Japan	1997	0.288	0.016	0.083	0.112	0.033	7.270	0.862
Japan	1998	0.288	0.011	0.058	0.068	0.035	10.563	0.905
Japan	1999	0.288	0.011	0.050	0.073	0.053	12.106	0.917
Japan	2000	0.288	0.019	0.050	0.132	0.152	13.696	0.927
Luxembourg	1996	0.365	0.060	0.083	0.210	0.053	3.970	0.748
Luxembourg	1997	0.365	0.016	0.083	0.112	0.031	7.305	0.863
Luxembourg	1998	0.365	0.011	0.058	0.068	0.028	10.581	0.905
Luxembourg	1999	0.365	0.011	0.050	0.073	0.050	12.118	0.917
Luxembourg	2000	0.365	0.019	0.050	0.132	0.114	13.703	0.927
Netherlands	1996	0.333	0.060	0.083	0.210	0.048	3.952	0.747
Netherlands	1997	0.333	0.016	0.083	0.112	0.022	7.292	0.863
Netherlands	1998	0.333	0.011	0.058	0.068	0.022	10.575	0.905
Netherlands	1999	0.333	0.011	0.050	0.073	0.038	12.114	0.917
Netherlands	2000	0.333	0.019	0.050	0.132	0.107	13.701	0.927
NZ	1996	0.336	0.060	0.083	0.210	0.064	3.965	0.748
NZ	1997	0.336	0.016	0.083	0.112	0.029	7.301	0.863
NZ	1998	0.336	0.011	0.058	0.068	0.041	10.578	0.905
NZ	1999	0.336	0.011	0.050	0.073	0.032	12.117	0.917
NZ	2000	0.336	0.019	0.050	0.132	0.119	13.703	0.927
Norway	1996	0.392	0.060	0.083	0.210	0.070	3.962	0.748
Norway	1997	0.392	0.016	0.083	0.112	0.035	7.298	0.863
Norway	1998	0.392	0.011	0.058	0.068	0.044	10.577	0.905
Norway	1999	0.392	0.011	0.050	0.073	0.049	12.116	0.917
Norway	2000	0.392	0.019	0.050	0.132	0.143	13.702	0.927
Portugal	1996	0.246	0.060	0.083	0.210	0.048	3.969	0.748
Portugal	1997	0.246	0.016	0.083	0.112	0.028	7.304	0.863
Portugal	1998	0.246	0.011	0.058	0.068	0.034	10.580	0.905
Portugal	1999	0.246	0.011	0.050	0.073	0.049	12.118	0.917
Portugal	2000	0.246	0.019	0.050	0.132	0.121	13.703	0.927
Spain	1996	0.217	0.060	0.083	0.210	0.032	3.965	0.748
Spain	1997	0.217	0.016	0.083	0.112	0.023	7.299	0.863
Spain	1998	0.217	0.011	0.058	0.068	0.027	10.578	0.905
Spain	1999	0.217	0.011	0.050	0.073	0.044	12.116	0.917
Spain	2000	0.217	0.019	0.050	0.132	0.123	13.702	0.927
Sweden	1996	0.803	0.060	0.083	0.210	0.101	3.955	0.747
Sweden	1997	0.803	0.016	0.083	0.112	0.051	7.294	0.863
Sweden	1998	0.803	0.011	0.058	0.068	0.051	10.576	0.905
Sweden	1999	0.803	0.011	0.050	0.073	0.056	12.115	0.917
Sweden	2000	0.803	0.019	0.050	0.132	0.141	13.702	0.927
Switzerland	1996	0.845	0.060	0.083	0.210	0.103	3.962	0.748
Switzerland	1997	0.845	0.016	0.083	0.112	0.049	7.299	0.863
Switzerland	1998	0.845	0.011	0.058	0.068	0.047	10.578	0.905
Switzerland	1999	0.845	0.011	0.050	0.073	0.064	12.117	0.917
Switzerland	2000	0.845	0.019	0.050	0.132	0.127	13.703	0.927
UK	1996	0.627	0.060	0.083	0.210	0.090	3.924	0.745
UK	1997	0.627	0.016	0.083	0.112	0.043	7.271	0.862
UK	1998	0.627	0.011	0.058	0.068	0.039	10.566	0.905
UK	1999	0.627	0.011	0.050	0.073	0.058	12.107	0.917
UK	2000	0.627	0.019	0.050	0.132	0.123	13.698	0.927
US	1996	0.551	0.060	0.083	0.210	0.072	3.321	0.699
US	1997	0.551	0.016	0.083	0.112	0.031	6.826	0.854
US	1998	0.551	0.011	0.058	0.068	0.033	10.270	0.903

(i) Country	(ii) Year	(iii) A_C	(iv) T	(v) σ	(vi) μ	(vii) R	(viii) IES	(ix) γ
US	1999	0.551	0.011	0.050	0.073	0.044	11.886	0.916
US	2000	0.551	0.019	0.050	0.132	0.117	13.552	0.926

Column (viii) reports the calculated *IES* values. Because of the presence of a country-specific effect which is economically small but which is retained on statistical grounds following a likelihood ratio test, there is some minor variation across countries in the size of the *IES*. However, the major result is the strong rise in the *IES* over time. This rise is significant, as indicated by the likelihood ratio test on the significance of the difference in the underlying parameters controlling the variability in the *IES*, and is directly attributable to world network externalities in consumption. As a further aid to economic interpretation, Column (ix) translates the *IES* back to the implied value of the coefficient γ in the power utility function. Over the sample period, the power function rises from around 0.75 for most countries in 1996 to 0.93 in 2000. Based on the estimated value of 16.657 for θ_2, which is the estimated asymptotic limit for the *IES*, the power term γ in the utility function will asymptote to 0.94 as network size increases indefinitely. This indicates that the long-run optimal degree of consumption externality has already been effectively extracted. Additions to the network will not increase the degree of the consumption externality to any appreciable extent.

V. CONCLUSION

A driving force behind the emergence of the "new" or information economy is the growth of Internet network capacity. However, a more fundamental problem in mapping this dynamic is the lack of an acceptable theoretical framework through which to direct empirical investigations of Internet network host evolution. Most of the models in the literature on network externalities have been developed in a static framework, with externalities viewed as instantaneous or self-fulfilling. The model specified here builds on received theory from several sources to include these features and develops a model that is both capable of econometric estimation and which provides as an output a direct measure of the network effect. Accordingly, the main goal of this paper is to find the magnitude of the external effect on Internet network growth. In addition, this paper illustrates the ability of panel data to generate estimates of structural parameters capable of explaining Internet host growth.

Estimates of an endogenous growth model in which sustained Internet system growth are the result of consumption and production externalities from the existence of network infrastructure are presented. Estimation of that model on a sample for OECD member states show the model results are compatible with Internet host growth data. To summarize the results, both production and consumption externalities are strongly in evidence in this model. Production externalities have been modeled relatively simply, but they nevertheless indicate a substantial degree of increasing returns to scale. On the consumption side, the possibility of the degree of the externality varying with the size of the network has been examined. Over the period, the strength of the consumption externality has grown and it now seems to be very close to its projected maximum strength. Further, in finding the preferred specification, pains have been taken to ensure that the model provides economically sensible values of core model outputs (including variable parameter estimates) related to the production and utility functions of the representative agent.

Several issues have been raised as a result of this investigation. In particular, on the consumption side there is some evidence that the optimal size of the network has been reached. This suggests that consumer driven Internet network growth may have reached a plateau. On the production side the specification used follows the received literature that generally considers the production externality is treated as a scale effect for a modified linearly homogeneous production function. An ambitious task then remains to consider both these effects in a more general setting, so as to allow examination as to the ultimate optimal network size. Finally, the model suggests that the traditional notion of critical mass needs to be modified in the context of the Internet to allow for both local and global critical masses, and taking account of the dynamic context in which Internet infrastructure decisions are made.

REFERENCES

Bensaid, B. and Lesne, J.-P. (1996), 'Dynamic Monopoly Pricing with Network Externalities', *International Journal of Industrial Organization*, 14, 837-855.

Bourreau, M. (2001), 'The Economics of Internet Flat Rates', *Communications and Strategies*, 42, 131 152.

Cooper, R.J., Madan, D.B. and McLaren, K.R. (1995), 'Approaches to the Solution of Stochastic Intertemporal Consumption Models', *Australian Economic Papers*, 34, 86-103.

Economides, N. (1996), 'The Economics of Networks', *International Journal of Industrial Organization*, 14, 673-699.

Economides, N. and Himmelberg, C. (1995), 'Critical Mass and Network Size with Application to the US FAX Market', Discussion Paper EC-95-11, Stern School of Business, New York University.

Economides, N. and White, L.J. (1994), 'Networks and Compatibility: Implications for Antitrust', *European Economic Review*, 38, 651-662.

Faulhaber, G.R. (1999), 'Emerging technologies and Public Policy: Lessons from the Internet', mimeo.

Gandal, N. (1995), 'Competing Compatibility Standards and Network Externalities in the PC Software Market', *Review of Economics and Statistics*, 77, 599-608.

IMF. (2000), *International Financial Statistics*, IMF, Washington, D.C.

ITU. (2001), *World Telecommunication Development Report*, ITU, Geneva.

Katz, M.L. and Shapiro, C. (1986), 'Technology Adoption in the Presence of Network Externalities', *Journal of Political Economy,* 94, 823-841.

Litan, R.E. and Rivlin, A.M. (2001), 'Projecting the Economic Impact of the Internet', *American Economic Review*, *AEA Papers and Proceedings*, 91, 313-317.

Littlechild, S.C. (1975), 'Two-part Tariffs and Consumption Externalities', *Bell Journal of Economics and Management Science,* 6, 661-670.

Markus, M.L. (1990), 'Critical Mass Contingencies for Telecommunications Consumers', in Carnevale, M., Lucertini, M. and Nicosia, S. (eds), *Modelling the Innovation: Communications, Automation and Information Systems*, IFIP.

Oren, S. and Smith, S. (1981), 'Critical Mass and Tariff Structure in Electronic Telecommunications Market', *Bell Journal of Economics and Management Science*, 12, 467-487.

OECD. (2000b), *Outlook 2000*, number 67, OECD, Paris.

OECD. (2001), *OECD Communications Outlook 2001*, OECD, Paris.

OECD. (1999), *OECD Communications Outlook 1999*, OECD, Paris.

OECD. (1997), *OECD Communications Outlook 1997*, Volume 1, OECD, Paris.

Rappoport, P.N., Kridel, D.J., Taylor, L.D., Alleman, J. and Duffy-Deno, K. (2002), 'Residential Demand for Access to the Internet' in Madden, G. (ed.), *The International Handbook of Telecommunications Economics: Volume II*, Edward Edgar Publishers, Cheltenham.

Rohlfs, J. (1974), 'A Theory of Interdependent Demand for a Communications Service', *Bell Journal of Economics and Management Science,* 5, 16-37.

Schoder, D. (2000), 'Forecasting the Success of Telecommunication Services in the Presence of Network Effects', *Information Economics and Policy,* 12, 155-180.

Shy, O. (2001), *The Economics of Network Industries*, Cambridge University Press, Cambridge.

White, K. J. (1997), SHAZAM User's Reference Manual Version 8.0, McGraw-Hill. ISBN 0-07-069870-8.

APPENDIX TABLE I. SOURCE AND CONSTRUCTED DATA

Country	Year	Price	Wage	HOSTS	ΔHOSTS	$HOSTS_{-1}$
Australia	1996	22.09	0.4801	514,760	205,198	309,562
Australia	1997	33.53	0.4859	665,403	150,643	514,760
Australia	1998	43.76	0.4916	792,351	126,948	665,403
Australia	1999	43.39	0.4810	1,090,468	298,117	792,351
Australia	2000	43.42	0.4787	1,615,939	525,471	1,090,468
Austria	1996	55.40	0.5281	88,811	35,467	53,344
Austria	1997	75.43	0.5215	108,473	19,662	88,811
Austria	1998	83.10	0.5230	172,569	64,096	108,473
Austria	1999	73.41	0.5229	262,632	90,063	172,569
Austria	2000	46.10	0.5178	483,208	220,576	262,632
Belgium	1996	46.81	0.5169	65,064	34,443	30,621
Belgium	1997	70.85	0.5119	106,808	41,744	65,064
Belgium	1998	87.60	0.5099	208,665	101,857	106,808
Belgium	1999	80.53	0.5110	339,357	130,692	208,665
Belgium	2000	56.90	0.5095	300,193	–39,164	339,357
Canada	1996	26.47	0.5142	603,325	230,434	372,891
Canada	1997	31.18	0.5185	839,141	235,816	603,325
Canada	1998	38.14	0.5262	1,119,172	280,031	839,141
Canada	1999	35.89	0.5115	1,669,664	550,492	1,119,172
Canada	2000	40.73	0.5062	2,364,014	694,350	1,669,664
Denmark	1996	35.20	0.5326	106,732	56,175	50,557
Denmark	1997	40.95	0.5334	169,368	62,636	106,732
Denmark	1998	38.94	0.5379	298,275	128,907	169,368
Denmark	1999	42.92	0.5399	338,239	39,964	298,275
Denmark	2000	25.87	0.5258	333,978	–4,261	338,239
Finland	1996	23.16	0.4996	314,141	98,437	215,704
Finland	1997	26.19	0.4864	486,811	172,670	314,141
Finland	1998	23.76	0.4841	459,568	–27,243	486,811
Finland	1999	29.38	0.4855	461,760	2,192	459,568
Finland	2000	30.43	0.4631	529,261	67,501	461,760
France	1996	31.72	0.5213	236,874	85,701	151,173
France	1997	47.72	0.5193	355,031	118,157	236,874
France	1998	59.30	0.5184	511,193	156,162	355,031
France	1999	54.75	0.5209	1,233,071	721,878	511,193
France	2000	34.44	0.5243	1,122,407	–110,664	1,233,071
Germany	1996	41.54	0.5559	691,864	217,489	474,375
Germany	1997	52.43	0.5417	1,132,174	440,310	691,864
Germany	1998	53.98	0.5321	1,449,915	317,741	1,132,174
Germany	1999	40.07	0.5328	1,635,067	185,152	1,449,915
Germany	2000	33.48	0.5343	2,040,437	405,370	1,635,067
Greece	1996	70.00	0.3207	16,738	8,997	7,741
Greece	1997	72.67	0.3299	28,131	11,393	16,738
Greece	1998	66.42	0.3420	49,904	21,773	28,131
Greece	1999	81.77	0.3411	75,088	25,184	49,904
Greece	2000	54.61	0.3427	110,608	35,520	75,088
Iceland	1996	24.52	0.5113	11,542	3,232	8,310
Iceland	1997	31.37	0.5015	18,520	6,978	11,542
Iceland	1998	35.72	0.5207	24,794	6,274	18,520
Iceland	1999	35.93	0.5288	29,872	5,078	24,794
Iceland	2000	28.62	0.5367	39,901	10,029	29,872
Ireland	1996	73.34	0.4474	26,895	13,460	13,435

Country	Year	Price	Wage	HOSTS	ΔHOSTS	$HOSTS_{-1}$
Ireland	1997	82.27	0.4275	39,864	12,969	26,895
Ireland	1998	75.85	0.4039	55,859	15,995	39,864
Ireland	1999	64.92	0.4098	63,913	8,054	55,859
Ireland	2000	61.00	0.3938	110,545	46,632	63,913
Italy	1996	48.85	0.4252	147,873	72,497	75,376
Italy	1997	49.36	0.4273	254,296	106,423	147,873
Italy	1998	40.81	0.4091	386,632	132,336	254,296
Italy	1999	43.53	0.4119	301,528	–85,104	386,632
Italy	2000	38.06	0.4043	1,019,711	718,183	301,528
Japan	1996	22.90	0.5536	734,406	465,079	269,327
Japan	1997	31.68	0.5583	1,168,956	434,550	734,406
Japan	1998	35.17	0.5653	1,687,534	518,578	1,168,956
Japan	1999	24.25	0.5598	2,636,541	949,007	1,687,534
Japan	2000	22.87	0.5640	4,640,863	2,004,322	2,636,541
Luxembourg	1996	38.64	0.5317	3,518	1,638	1,880
Luxembourg	1997	53.91	0.5117	4,743	1,225	3,518
Luxembourg	1998	61.29	0.5067	7,737	2,994	4,743
Luxembourg	1999	84.24	0.5005	9,614	1,877	7,737
Luxembourg	2000	59.93	0.4920	11,814	2,200	9,614
Netherlands	1996	45.16	0.5350	270,511	98,746	171,765
Netherlands	1997	55.06	0.5315	391,228	120,717	270,511
Netherlands	1998	54.45	0.5306	625,769	234,541	391,228
Netherlands	1999	48.07	0.5169	959,083	333,314	625,769
Netherlands	2000	52.90	0.5167	1,623,567	664,484	959,083
NZ	1996	55.41	0.4368	84,532	30,922	53,610
NZ	1997	58.55	0.4398	169,264	84,732	84,532
NZ	1998	56.61	0.4390	137,247	–32,017	169,264
NZ	1999	50.32	0.4441	271,003	133,756	137,247
NZ	2000	53.62	0.4430	345,107	74,104	271,003
Norway	1996	27.16	0.4596	150,130	65,836	84,294
Norway	1997	34.04	0.4678	292,382	142,252	150,130
Norway	1998	39.19	0.5017	318,993	26,611	292,382
Norway	1999	37.93	0.4964	438,961	119,968	318,993
Norway	2000	39.07	0.4444	452,677	13,716	438,961
Portugal	1996	135.69	0.4290	23,482	11,706	11,776
Portugal	1997	116.40	0.4313	42,447	18,965	23,482
Portugal	1998	79.35	0.4397	55,746	13,299	42,447
Portugal	1999	108.09	0.4279	77,761	22,015	55,746
Portugal	2000	74.05	0.4347	62,147	–15,614	77,761
Spain	1996	53.54	0.5225	113,227	61,771	51,456
Spain	1997	54.46	0.4980	196,403	83,176	113,227
Spain	1998	45.13	0.5003	306,559	110,156	196,403
Spain	1999	58.56	0.5026	469,587	163,028	306,559
Spain	2000	58.62	0.5061	455,487	–14,100	469,587
Sweden	1996	22.65	0.5895	237,832	92,988	144,844
Sweden	1997	31.59	0.5631	348,609	110,777	237,832
Sweden	1998	39.64	0.5648	379,455	30,846	348,609
Sweden	1999	33.76	0.5613	522,888	143,433	379,455
Sweden	2000	33.56	0.5612	595,698	72,810	522,888
Switzerland	1996	29.22	0.6034	132,925	52,791	80,134
Switzerland	1997	38.35	0.6063	189,175	56,250	132,925
Switzerland	1998	44.13	0.6074	245,409	56,234	189,175
Switzerland	1999	41.34	0.6044	269,812	24,403	245,409

Country	Year	Price	Wage	HOSTS	ΔHOSTS	$HOSTS_{-1}$
Switzerland	2000	29.58	0.5942	262,510	–7,302	269,812
UK	1996	57.71	0.5351	719,333	279,565	439,768
UK	1997	59.96	0.5369	987,733	268,400	719,333
UK	1998	60.07	0.5437	1,449,315	461,582	987,733
UK	1999	52.87	0.5524	1,739,078	289,763	1,449,315
UK	2000	36.79	0.5577	1,677,946	–61,132	1,739,078
US	1996	28.06	0.5756	10,112,888	4,057,929	6,054,959
US	1997	32.17	0.5603	20,623,996	10,511,108	10,112,888
US	1998	37.18	0.5689	30,489,464	9,865,468	20,623,996
US	1999	32.18	0.5699	53,175,956	22,686,492	30,489,464
US	2000	18.96	0.5659	80,566,944	27,390,988	53,175,956
World	1996			16,249,917		9,485,918
World	1997			30,127,576		16,249,917
World	1998			43,547,090		30,127,576
World	1999			72,010,326		43,547,090
World	2000			106,724,179		72,010,326