The economic impact of broadband: evidence from OECD countries

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1. Introduction

The key aim of this report is to measure the economic impact of broadband[1] using an econometric method that accounts for the dual nature of the underlying effect: the economic impact as a result of increased broadband use and the effects that higher incomes have on broadband adoption. There are several ways to model this link ranging from experimental designs with treatment variations to growth accounting using macroeconomic data. In the absence of microeconomic data a standard approach involves the use of different stages in the estimation of the effects. In this report I use the structural framework proposed by Roller and Waverman (2001) and Koutroumpis (2009).

This model measures the direct and reverse effect of broadband use on the local economy combining an aggregate production function with a micro-model of supply, demand and output. This report replicates the model used in Koutroumpis (2009) and updates its findings using an OECD panel of countries for the period 2002 to 2016. In this report I first present the econometric framework that mimics the way broadband affects the national economy. I then set out the data series and their sources before presenting the results. The study also discusses potential limitations and caveats that should be considered.

The final purpose of this report is to increase Ofcom's understanding of the impact of faster broadband on economic growth and translate this to quantified potential impacts of previous investments.

[1] Broadband is defined as any type of internet connection (fixed or mobile) capable of providing a minimum of 256Kbits/s of data throughput. This is the official ITU definition.

2. The model

As stated in the introduction this report replicates the model set out in the Koutroumpis (2009) paper. The model is composed of an aggregate production function which links national aggregate economic output GDP_{it} to a set of production factors in each country *i* at time *t.* In particular the stock of capital (K), labour (L) and the stock of broadband and fixed telecommunications infrastructure. The stock of broadband infrastructure is used rather than the broadband investment because consumers demand infrastructure and not investment *per se*. Since the expected growth effects deriving from broadband accrue from the use of the infrastructure I approximate these effects through the level of broadband adoption (BB_Pen).[2]

<u>Aggregate production function</u>

$$GDP_{it} = f(K_{it}, L_{it}, BB\_Pen_{it}) \qquad (1)$$

Real GDP thus is a function of labour force, capital stock and broadband infrastructure. While the coefficients for labour (L) and capital (K) should be typical for production functions, the coefficient of broadband penetration in equation (1) estimates the one-way causal relationship flowing from the stock of broadband telecommunications infrastructure to aggregate GDP. In order to disentangle the possible effects of broadband telecommunications infrastructure on GDP from the effects of GDP on broadband telecommunications infrastructure, I specify a micro-model for the telecommunications sector in each country consisting of three equations for demand and supply of broadband infrastructure, as well as an infrastructure output function[3].

<u>Demand for broadband infrastructure:</u>

$$BB\_Pen_{it} = g(GDPC_{it}, BBPr_{it}, EDU_{it}, RD_{it}, Urb_{it}) \qquad (2)$$

The demand equation (2) links broadband penetration as a function of GDP per capita (GDPC), the price of the broadband service[4] (BBPr) and other parameters that affect the propensity to adopt broadband technologies, namely the education level in country *i,* the percent of GDP invested in research and development (R&D) and the level of urbanization (Urb).

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[2] References are given in Table 1 below

[3] Diagnostic tests for multicollinearity are discussed in the Appendix and tables A3 – A5

[4] This variable is collected from ITU (WTID) and is defined as the monthly connection charge for fixed (wired) broadband internet service. Fixed broadband service is considered to be any dedicated connection to the internet with downstream speeds equal to or greater than 256 Kbits/s. If several offers are available preference will be given to the 256 Kbits/s (or other minimum connection speed).

Similarly, for broadband speed, fixed broadband speed in Mbits/s refers to the advertised maximum theoretical download speed and not speeds guaranteed to users associated with a fixed –broadband Internet monthly subscription.

Supply of broadband infrastructure:

$$BB\_Inv_{it} = h(BBPr_{it}, HHI_{it}) \quad (3)$$

Modeling the supply of fixed telecommunications infrastructure is not always straightforward. Coverage of high-speed networks depends on operators' strategic decisions as well as the socio-economic and geographic parameters. Equation (3) can thus be seen as a stylized representation of the supply side. Broadband investment per capita (BB_Inv_{it}) in a country is linked to broadband prices for that period and to competition across technologies. To measure competition across different technologies I estimate the Hirschman Herfindahl Index (HHI) for the relative shares of copper, cable, fibre and other networks in each country. The index ranges from zero to one: in a fully concentrated market where all subscribers use a single platform the index equals 1. As more platforms are used and subscribers are more evenly distributed across networks the HHI approaches zero.

Broadband infrastructure production function:

$$\Delta BB\_Pen_{it} = k(BB\_Inv_{it}) \qquad (4)$$

The infrastructure equation (4) states that the annual change in broadband penetration is a function of the broadband investment per capita, taken as a proxy of the capital invested in a country during one year. The infrastructure increase is modeled as a function of investment, as this should be the main source of funding of infrastructure growth by broadband firms. Equations (2), (3) and (4) endogenize broadband telecommunications infrastructure because they involve the supply and demand of broadband telecommunications services. The econometric specification of the model is as follows:

Aggregate Production equation:

$$\log(GDP_{it}) = a_1 \log(K_{it}) + a_2 \log(L_{it}) + a_3 \log(BB\_Pen_{it}) + \varepsilon_1$$

Demand equation:

$$\log(BB\_Pen_{it}) = \beta_1 \log(GDPC_{it}) + \beta_2 \log(BBPr_{it}) + \beta_3 \log(EDU_{it}) + \beta_4 \log(RD_{it}) + \beta_5 \log(Urb_{it}) + \varepsilon_2$$

Supply equation:

$$\log(BB\_Inv_{it}) = \gamma_1 \log(BBPr_{it}) + \gamma_2 HHI_{it} + \varepsilon_3$$

Broadband infrastructure production equation:

$$\log(\Delta BB_{Pen_{it}}) = \delta_1 \log(BB_{Inv_{it}}) + \varepsilon_4$$

The countries in the sample do not necessarily share the same characteristics with one another in terms of local economic conditions, culture and other location-specific preferences. To account for this variation and to refrain from treating observations from different origins as otherwise identical, I add a full range of country fixed effects in the regressions (Table 2) that help capture these effects. Similarly, there may be temporal variations due to political, social or economic changes within countries that capture seasonal or cyclical trends and business cycles that are reflected in the panel data and would falsely be attributed to the measured phenomenon. I use year fixed effects in all specifications to capture these annual effects.

3. Data

Building on the work of the previous study, the dataset used in this study consists of annual observations from 35 countries for the fifteen-year period between 2002 and 2016. The countries included in the analysis used are listed in the appendix (Table A1). The data used have been collected by various sources depending on their nature and availability (see Table 1) as well as the summary statistics. The Hirschman-Herfindahl (HHI_{it}) market and technology concentration index for each country *i* is calculated[5] as the sum of the squares of market shares of all technologies in the market at time *t*.

Table 1. Data used in the analysis and sources

Variable	Source	Obs
GDP (constant 2010 US$)	OECD	525
GDP per capita (constant 2010 US$)	OECD	510
Gross fixed capital formation (% of GDP)	OECD	506
Fixed broadband subscriptions (per 100 people)	OECD	474
Fixed broadband Internet monthly subscription (US$)	ITU	523
Urban population (% of total)	OECD	510
Government expenditure on education, total (% of GDP)	OECD	387
Research and development expenditure (% of GDP)	OECD	386
Fixed (wired)-broadband speed; in Mbits/s	ITU	305
Annual investment in telecommunication services (US$)	ITU	418
Labour force participation rate, total (% of total population ages 15+) (modeled ILO estimate)	OECD	510
DSL Internet subscriptions	ITU	525
Fixed-broadband subscriptions	ITU	525
Cable modem Internet subscriptions	ITU	525
Fibre-to-the-home/building Internet subscriptions	ITU	525

[5] Author's calculations from annual data

4. Results

The baseline specification Eq. (1)-(4), confirms previous findings and reinforces our understanding of the impact of broadband on the economy (Table 2, Column 1)[6]. Labour and capital have the expected signs, significance and ratios for the set of observations used as they are both positive and highly significant for economic output. Broadband adoption enters the regression with a positive and highly significant coefficient too. On average the OECD sample grew from 3.8 connections per 100 people in 2002 to 31.3 connections per 100 people. The implied GDP impact from this change can be measured using Eq. (5), which links adoption levels and the coefficient for broadband α_3. Using this formula we can translate broadband adoption changes to increased economic output as it has been used in previous studies (see Roller and Waverman (2001), Koutroumpis (2009) and Gruber and Koutroumpis (2011)):

$$GDP_{BBPen} = 1 - e^{(logBBPen_{2016} - logBBPen_{2002}) * a_3} \quad (5)$$

I find that – during this period – the increase in broadband connections per 100 people contributed to a cumulative GDP increase of 4.34% for the countries in the sample. A ten-line increase from 20 to 30 lines per 100 people leads to a 0.82% GDP impact but the effect diminishes with higher adoption rates. An identical ten line increase from 10 to 20 lines yields 1.40%. This estimate is in line with previous findings by Koutroumpis (2009), Qiang and Rossoto (2009) and Czernich et al (2011).

Before moving further in the analysis it is important to explain how broadband affects GDP over time. Imagine two identical economies that only differ in broadband adoption. Apart from the levels, the rate of broadband adoption matters for GDP too. An identical 10-line increase in adoption per 100 people, yields the same GDP effect (level) irrespective of the period over which this is achieved; however a higher rate of increase in broadband leads to a higher annual impact on GDP over a shorter period. This growth rate is sustained until no more subscribers are interested in connecting to the network leading to a saturation point in adoption with no further increases in GDP, other things (especially speeds) being equal. The annual rate of GDP growth is given by Eq. (6) that helps annualize the level effects from increased adoption:

$$GDP_{BBPen\_annual} = \left\{e^{(logBBPen_{2016} - logBBPen_{2002}) * a_3}\right\}^{\frac{1}{\Delta t - 1}} \quad (6)$$

From this formula it is easy to estimate that a 10 line increase (from 20 to 30 lines) over 5 years yields a 0.2% GDP impact whereas the same change over 10 years yields only 0.09%. The overall effect remains the same but the rate is affected. For the entire period (2002-2016) in the OECD sample the implied GDP effect from broadband is 0.30% per annum on average. For the UK the effect was 0.37%

[6] Column 2 of Table 2 presents results which distinguish between different line speeds. The results for this specification of the model are discussed on page 8.

per annum on average, with a total impact of 5.28% (moving from 3 lines per 100 people in 2002 to 38.6 in 2016).

Table 2. Econometric results broadband impact, by quality of connections and penetration rate

Variables	3SLS estimates (1)	3SLS estimates (2)
Production (GDP_{it})		
Fixed stock of capital (K_{it})	0.152***	0.153***
	(0.0272)	(0.0269)
Labour (L_{it})	0.848***	0.823***
	(0.162)	(0.160)
Broadband Lines (BB_Pen_{it})	0.0464**	0.0482**
	(0.0201)	(0.0198)
Broadband Speed (BB_Speed_{it})	-	0.0147**
		(0.00613)
Demand (PEN_{it})		
GDPC ($GDPC_{it}$)	0.286***	0.287***
	(0.0953)	(0.0953)
BB. Price (BB_Pr_{it})	-0.501***	-0.502***
	(0.113)	(0.113)
Urbanization	-0.062***	-0.0606***
	(0.0233)	(0.0233)
R&D	0.521***	0.520***
	(0.0874)	(0.0874)
Education level	0.507***	0.508***
	(0.196)	(0.196)
Supply (BB_Inv_{it})		
BB Price (BB_Pr_{it})	0.367***	0.368***
	(0.117)	(0.117)
HHI (HHI_{it})	0.583***	0.583***
	(0.188)	(0.188)

Output (ΔPen_{it})		
BB Investment	0.150***	0.153***
(BB_Inv_{it})	(0.00160)	(0.0579)
Controls		
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	241	241

To maintain this momentum once broadband adoption reaches a saturation point, the intensive margin of the infrastructure has to be exploited through improvements in quality that enable the use of a wider range of services[7]. Since this first estimate (Table 2, column 1) isolates the effect of increased adoption from any other quality improvements that may have taken place during this period I further introduce the speed variables in the regression. For this I add a broadband speed variable in the production function (see Table 2, column 2) to assess the variations in quality of broadband access on GDP. Speed is not strictly exogenous as wealthier countries may indeed have higher quality of connections. To proceed with this analysis, I assume that any reverse effect from GDP on speed is largely absorbed by the adoption variable. The production function now becomes:

$$\log(GDP_{it}) = a_1 \log(K_{it}) + a_2 \log(L_{it}) + a_3 \log\left(BB_{Pen_{it}}\right) + a_4 \log(BB\_Speed_{it}) + \varepsilon_1$$

The speed coefficient (measured in Mbits/s) enters the regression with a positive and significant coefficient as expected. This estimate implies that, possibly, part of the quality improvements at the country level had been captured by country and year controls in the adoption-only results. Substituting adoption with speed in a modified version of Eq. (5) I estimate that increasing speeds from 2Mbits/s to 8Mbits/s adds 0.9% on GDP. If this change happens over a period of 10 years it leads to an annual GDP increase of 0.10% on top of any changes in adoption. A country that achieves this transition in 5 years will increase its annual GDP by 0.22% leading to a higher annual GDP increase for a shorter period of time. Like adoption, the rate of speed increases matter for GDP as illustrated in this example. Overall the OECD region grew from a 0.75 Mbits/s speed in 2002 into 12.85 Mbits/s in 2016. The GDP change from this increase is 1.32% and the annualized effect 0.09% (the country level results are shown in Figure 1) . Combining the effect of the adoption and speed changes contributed 5.66% to OECD GDP in total over the period or 0.39% annually on average. For the UK, the speed

[7] The extensive margin refers to the increase in adoption and the intensive margin to increases in quality (including speed) increases.

increase contributed 1.71% to GDP in total and 0.12% annually. Combining the effect of the adoption and speed changes increased UK GDP by 6.99% cumulatively and 0.49% annually on average.

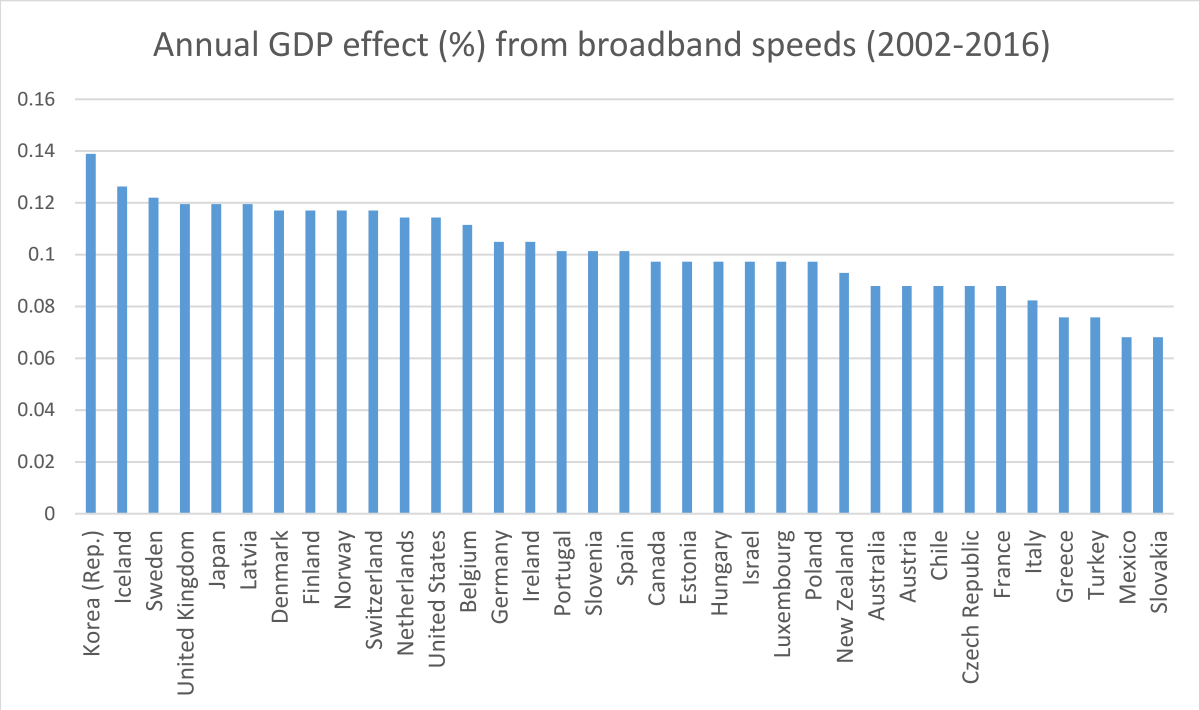
Moving further I also test the possibility of a non-linear (higher order polynomial) relationship between speed increases and GDP using a quadratic speed variable in the production function (Table A2, column 2). The negative and significant coefficient in the quadratic term shows that speed has diminishing returns on GDP. In fact I find that – for the average country in the sample – the highest effects from speed are realized up to a certain speed level. For the time period under consideration, this level is at the maximum of the inverted u-shaped curve with a peak of 9.8Mbits/s.[8] The implied effect suggests that there was little – if any – effect for further investments beyond this point. This speed threshold varies across countries and over time though. For example, some economies may be able to utilize higher levels of speed during this period and others may be unable to make productive use of even lower levels. This heterogeneity is explained through the "readiness" of the economy to transform the quality of infrastructure into economic outcomes. Taking this observation into consideration reduces the overall GDP effect for the OECD sample to 0.38% annually or 5.49% in total. The adoption effect remains at 4.34% in total while the speed effect drops from 1.32% to 1.15% in total, and from 0.09% to 0.08% annually on average. For the UK, the overall GDP effect reduces to 0.47% annually and 6.67% in total. The adoption effect remains the same but the speed effect reduces from 1.71% to 1.38% in total and from 0.12% to 0.10% annually on average. The upper speed threshold may be increasing over time as new services appear that help firms and individuals productively use the improved infrastructures.

It is important to note here that broadband speeds can also reach a saturation point. This may happen due to physical limitations of data transfer or because any further increase would make no economic sense (i.e. the data transfer protocols have improved so much that no further investments are necessary in fixed broadband infrastructure). In this case the GDP effects from broadband use can not be explained any further from this model. A country that has reached the saturation point in adoption and speed may experience additional GDP effects but these would not be attributed to the networks anymore. The model used in this analysis and Eq. (6) indicates that any residual GDP returns beyond this point would be attributed to new products and services and not the underlying network that enabled them to appear. This is in line with the impact of other essential but often saturated infrastructures like the road transport network, the electricity grid or the water distribution system.

For example, countries with lower average speeds over the period 2002-2016 had a smaller GDP impact from the use of the networks (other things being equal). In Mexico with an average speed of 1.16 Mbits/s and Turkey with 1.84 Mbits/s the annual GDP impact from broadband speeds ranged from around 0.06% to around 0.07%. At the other extreme Korea and Japan, closely followed by Sweden and the UK, have been leading in terms of network quality and speeds (11.58 Mbits/s and 7.88 Mbits/s respectively for the period). This has helped them increase their relative gains between 0.12%-0.14% on an annual basis.

[8] The cap is an average across OECD countries, it may differ by country though I am unable to estimate this at country level. This cap is estimated at 3Mbits/s in 2011 and 6.7Mbits/s in 2014, i.e. it has been increasing over time.

Figure 1: The annual GDP impact of broadband by country[9]



Looking into the rest of the results from Table 2 (column 1 and 2), the demand and supply functions also have the expected results with income as a major contributor to adoption and supply of broadband services. I find that the overall broadband demand proxied by the country level adoption per year is positively linked to income per capita. Broadband prices enter the demand equation with a negative and significant sign confirming the previously found (Koutroumpis, 2009) relatively inelastic relationship with broadband adoption.

Urbanization has a negative effect on adoption, which seems counter-intuitive. Investment in broadband networks in urban areas is often more cost-effective and the services offered over the Internet cover urban areas more quickly. Hence it would have been expected that higher urbanization leads to increased broadband adoption. Looking at the variable itself, it is defined as the share of inhabitants in – nationally defined – urban and suburban regions. This lack of a common standard on the definition of regions limits the predictive power of this metric especially in cross-country comparisons[10].

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[9] These speed effects are not constrained by second order effects. If they were then the theoretical upper bound of speed impacts on GDP would reach a maximum of 0.11% per annum (if a country started with no broadband in 2002), or an actual upper bound of around 0.1% per annum. However that would assume that the 9.8Mbits/s upper threshold is the same across all OECD countries.

[10] There are various limitations in measuring urbanization according to the World Bank (2017): "Aggregation of urban and rural population may not add up to total population because of different country coverage. There is no consistent and universally accepted standard for distinguishing urban from rural areas, in part because of the wide variety of situations across countries. Most countries use an urban classification related to the size or characteristics of settlements. Some define urban areas based on the presence of certain infrastructure and services. And other countries designate urban areas based on administrative arrangements. Because of national differences in the characteristics that distinguish urban from rural

The other variables in this regression including the average education level in a country and the expenditures in R&D seem to be positively linked to higher levels of broadband adoption in line with expectations.

The supply equation links the normalized (per capita) annual investment in broadband networks with prices and infrastructure competition. Prices are positively linked to adoption suggesting that, perhaps unsurprisingly, network operators prefer to invest in places where higher revenues are expected. Similarly the more concentrated a market is the higher the propensity to invest, i.e. operators prefer markets with one rather than more competing broadband networks. This link is not linear though; the relationship between market concentration and investment is an inverted U-shaped curve (indicated by a negative quadratic HHI coefficient) with lower investment per capita in a very fragmented or highly monopolized market and higher investments per capita in competitive oligopolies (see Table A2 in the Appendix).

The output equation links broadband investment with the difference in adoption per year. As expected the increase in investment (e.g. in coverage or quality) has a positive and significant footprint on overall adoption.

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areas, the distinction between urban and rural population is not amenable to a single definition that would be applicable to all countries. Estimates of the world's urban population would change significantly if China, India, and a few other populous nations were to change their definition of urban centres. Because the estimates of city and metropolitan area are based on national definitions of what constitutes a city or metropolitan area, cross-country comparisons should be made with caution”. World Bank Data Portal (data.worldbank.org, accessed November 2017)

5. Discussion

In this section I discuss some potential policy implications deriving from the findings and I also look into the limitations of this exercise.

The findings of this study confirm that broadband adoption affects the economy and that the quality of networks plays a significant role in this process. It is further shown that, for the time period under consideration, the returns from increasing speeds on GDP are positive but diminishing (Table 2 and Table A2). The upper threshold of speed related gains is moving higher as a result of the "readiness" of the economy (individuals or firms) to make productive use of improved infrastructures through the availability of services that demand more bandwidth. This is an important policy implication when future broadband strategies are considered. The main rationale of this finding rests with standard economic intuition. Every economy consists of a set of resources and skills that determine its economic capacity: on the extensive margin production can only increase if more labour (of identical skills) or capital is put in place. Still, there are various technologies that help the economy produce more by coordinating its activities, reducing communication costs and improving market conditions by increasing its capital and labour intensive margins (producing more from a more efficient use of the *same* resources). For the analysis we conducted the maximum GDP effects are found where countries moved from the relatively lowest speeds to the relatively highest speeds over the period 2002-2016.[11]

As well as the potential for diminishing returns to speed, it is shown that broadband as a network technology has a measureable effect on economic output. Through information exchange, new services and telework it has helped increase GDP by an average of 0.38% each year for the OECD countries. We show that this effect is related to the quality of infrastructure. On average a country at the highest speeds (capped by the 9.8Mbits/s threshold) would gain 0.08% more on its annual GDP compared to an identical country at the lowest speeds (the lowest quartile in the sample, which is 0-1Mbits/s). This corresponds approximately to a speed increase from 1Mbits/s to 10Mbits/s. Taking into account the diminishing returns to speed a similar change for a country starting from a higher speed in 2002 would have a smaller marginal effect.

Using this information, policy makers can adapt their strategies on two fronts, namely the effects of wider adoption until saturation and the relative merits of higher quality at various levels of adoption. Moreover, these findings provide the ground for comparison across countries and help plan future investments – with variations in public funding – as the costs and benefits accrue from a measureable impact on GDP.

Having analyzed the implications of the findings I discuss the possible data limitations and caveats related to the methodological design. In this analysis I used national level data – in the absence of more granular information – with the implicit assumption these can adequately represent the country level conditions. As it has often been observed[12] in the academic literature, there is higher

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[11] To compute this level for the highest cluster (the top quartile which had speeds >8Mbits/s) I modified Eq. (1) by adding a variable for speed and speed^2. The results are show in Table A2, Column2. The maximum speed is calculated by the maximum of the speed curve. Country fixed effects can affect this OECD-level interpretation; also the implied negative impacts of speed on GDP beyond the 9.8 Mbits/s should be handled as a plateau (see Ahlfeldt, et al 2017).

[12] See Acemoglu and Dell (2010) on productivity between and within countries; also Atkinson, Pikkety and Saez (2011) on inequality; Lakner and Milanovic (2015) on income distributions.

heterogeneity within countries than across them making these observations sensitive to outliers or other types of heavily skewed distributions. Along the same rationale, the use of one observation per year could be improved by more granular observations that help account for seasonal (pricing/advertising campaigns) or cyclical (exchange rates) events commonly found in the evolution of broadband adoption. A number of assumptions need to be made to carry out this analysis. For example, building a year by country panel assumes that there is one specific type of consumer that we observe that perfectly matches (or averages) the preferences of all types observed in this country and year.

Besides the limitations in data granularity there are other parameters that may affect the results. For example, it is not clear if all broadband plans are available to every user due to the presence – or lack thereof – of various operators across each country. Similarly, there is no information with regards to coverage suggesting that the option to adopt may not be offered to everyone in equal terms with regards to the technologies and networks available. Other national level observations presume a uniform distribution for investments in education or research. These effects may be driven by various factors like the presence of technological hubs or research centers often concentrated around to metropolitan areas or universities.

Beyond the information availability this exercise incorporates some methods that help measure the impact of broadband on the economy. Evaluation of specific interventions is best measured through quasi-experimental designs where the population is split in a randomly selected treatment and control group. Ideally we would prefer a setting with two identical areas – one with and one without broadband – to test the impact we are after. Since this is not possible I have used instead a closed form framework that mimics broadband market dynamics within an economy. This does not necessarily produce biased results but there can always exist omitted variables or are other confounding effects (apart from broadband) driving or diminishing the impact of connectivity (i.e. sub-national, cultural, technical, etc.)

Last it is important to state that in this modeling framework I have looked into the economic effects of broadband across countries. Other significant effects including life satisfaction and welfare have not been measured although we have evidence that access and use of the networks affects them[13].

[13] Kavetsos and Koutroumpis (2011); Graham and Nikolova (2013); Penard et al (2013)

References

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Appendix

Table A1: Countries included in the dataset

Australia	Hungary	Norway
Austria	Iceland	Poland
Belgium	Ireland	Portugal
Canada	Israel	Slovakia
Chile	Italy	Slovenia
Czech Republic	Japan	Spain
Denmark	Korea (Rep.)	Sweden
Estonia	Latvia	Switzerland
Finland	Luxembourg	Turkey
France	Mexico	United Kingdom
Germany	Netherlands	United States
Greece	New Zealand	

Table A2 provides some additional findings. In Column 1 a quadratic term for HHI is added to show the inverted U-shape curve that links competition and investments. In Column 2 a quadratic speed term is added to indicate the diminishing returns to speed (and the computation of the maximum level of impact at 9.8Mbits/s).

Table A2: Quadratic HHI and speed findings

Variables	**3SLS estimates**	**3SLS estimates**
	(1)	(3)
Production (GDP$_{it}$)		
Fixed stock of capital (K_{it})	0.147***	0.151***
	(0.027)	(0.0252)
Labour (L_{it})	0.829***	0.702***
	(0.161)	(0.160)
Broadband Lines (BB_Pen_{it})	0.0601***	
	(0.0191)	
Broadband Speed (BB_Speed)		0.0339***
		(0.00671)
Broadband Speed squared (BB_Speed)		-0.0172***
		(0.00251)
Demand (PEN$_{it}$)		
GDPC (GDPCit)	0.287***	0.300***
	(0.0952)	(0.0953)
BB. Price (BB_Prit)	-0.500***	-0.500***
	(0.113)	(0.113)
Urbanization	-0.0598**	-0.0610***
	(0.0233)	(0.0233)
R&D	0.521***	0.509***
	(0.0873)	(0.0875)
Education level	0.510***	0.499**
	(0.196)	(0.196)
Supply (BB_Inv$_{it}$)		
BB Price (BB_Pr_{it})	0.356***	0.366***
	(0.116)	(0.117)

HHI (HHI_{it})	1.143*	0.582***
	(0.692)	(0.188)
HHI^2 (HHI_{it})	-0.494	
	(0.611)	
Output (ΔPen_{it})		
BB Investment (BB_Inv_{it})	0.192***	0.154***
	(0.00704)	(0.0579)
Controls		
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	241	241

Tables A3 – A5 include tests for multicollinearity among regressors in the production, demand and supply equations. There are no indications of high standard errors or low t-statistics in the results. Additionally, I use Variance Inflation Factors that show most of the variance (1/VIF should be translated as percentages, i.e. 0.52 is 52%, etc.) is independent of other variables. Any collinear variables would not have been estimated in the first place.

Table A3: VIF for the production function

Variable	**VIF**	**1/VIF**
Broadband Penetration	1.92	0.520998
Speed	1.91	0.523638
Capital	1.06	0.939961
Labour	1.04	0.959603
Mean VIF	1.84	

Table A4: VIF for the demand function

Variable	VIF	1/VIF
GDPC ($GDPC_{it}$)	2.78	0.360108
R&D	2.36	0.423257
Education level	1.48	0.673881
BB Price (BB_Pr_{it})	1.31	0.765803
Urbanization	1.25	0.797819
Mean VIF	1.84	

Table A5: VIF for the supply function

Variable	VIF	1/VIF
HHI (HHI_{it})	1.04	0.965289
BB Price (BB_Pr_{it})	1.04	0.965289
Mean VIF	1.04	

Figure A1: The distribution of average broadband speeds in the sample

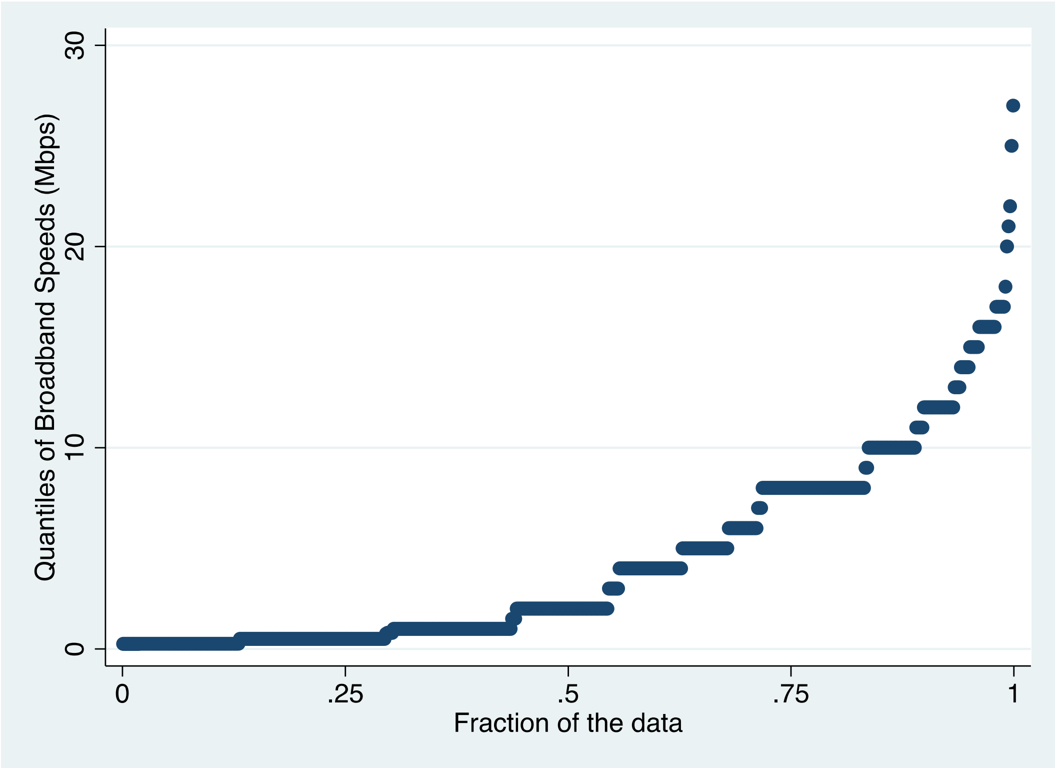

Figure A2: The evolution of average broadband speeds over time across all countries in the sample