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Literature Review of the Economic Impacts of Broadband

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Abstract

This comprehensive literature review examines the economic impacts of broadband, with a focus on productivity and economic growth. Incorporating 55 quantitative economic papers covering cross-country, firm-level, and industry studies, we provide detailed explanations of data choices, methodologies, and key findings. We explore various measures used to quantify broadband impacts, including penetration rates, speed, and technology adoption. We analyze studies on broadband's effects on total output, total factor productivity (TFP), employment, and the applications enabled by broadband, such as social media, e-commerce, and cloud computing. Methodological challenges, such as endogeneity and data limitations, are discussed, underscoring the need for improved methodologies and data to accurately assess broadband's economic impact. Overall, findings indicate a generally positive association between broadband penetration and output and labour productivity, despite some mixed results from earlier studies. More recent studies with improved methodologies consistently demonstrate a positive impact. Similarly, studies on TFP and employment reveal a positive influence of broadband.

Literature Review of the Economic Impacts of Broadband

Executive Summary

This literature review provides a comprehensive analysis of the economic impacts of broadband, focusing on productivity and economic growth. It includes 55 different quantitative economic papers from cross-country studies to firm-level and industry studies, and provides a detailed explanation of their data choices, methodology, and main findings.

We begin by discussing the various measures used in the literature to quantify the impacts of broadband. These measures include broadband penetration rates, broadband speed, and the adoption of broadband technologies by firms. We then look at four sets of studies.

First, we look at studies that measure the impact of broadband on total output. Although some earlier studies found mixed results, these studies have methodological shortcomings, and more recent studies have general found a positive association between broadband penetration and output.

Second, we look at studies that attempt to isolate the impact of broadband on total factor productivity (TFP), which essentially captures the extent to which investment creates spillovers to the broader economy that are not captured by the companies investing in broadband. These studies, particularly those the look across industries and countries rather than firms, also find a positive impact of broadband.

Third we look at the impact on employment, where the impact of broadband could be positive or negative, depending on the extent to which broadband displaces existing jobs. Studies that look at this area generally find positive impacts on employment, although this may not be true for less educated workers.

Finally, we emphasize that the economic impacts of broadband are not generated by broadband alone, but by the applications it enables, such as social media, e-commerce, and cloud computing. We therefore also look at the literature focusing on the applications of broadband in areas like telehealth, education, telework, agriculture, and civic engagement, which have been found to positively affect GDP and employment.

We then discuss some of the methodological problems that these studies can face. We discuss the endogeneity arising from the reverse causality between broadband and economic outcomes. This arises because greater use of broadband can stimulate economic growth, while higher incomes lead to more demand for broadband. This makes disentangling the relationship between broadband and economic growth less than straightforward. We also highlight potential issues with the simultaneous equation model often used to identify the causal impact of broadband on output and critique the use of broadband availability as an instrument for broadband adoption.

The review also discusses data limitations in estimating the impact of broadband, including the critique of the use of broadband penetration rate as an instrument for broadband adoption, and the advantages and disadvantages of firm-level data. A further challenge is disentangling the impact of broadband per se from the applications, such as cloud computing, which it enables, and which are the proximate cause of productivity growth. Unfortunately, data on broadband applications are extremely scarce.

While there are methodological challenges in estimating the impact of broadband, the literature generally supports the view that broadband has significant positive impacts on economic outcomes. Nevertheless, we emphasize the need for more robust methodologies and better data to accurately estimate the impact of broadband on the economy.

Literature Review of the Economic Impacts of Broadband[1]

The internet is a large part of everyday life in the 21st century, and the internet as we know it would not be possible without broadband and its precursors. Broadband has spurred many innovations, improved worker productivity and increased household consumer surplus (OECD, 2021).

The internet began in the 1980s with the beginnings of computers communicating with each other via USENET (Beckett, 2022). However, it was only available to those institutions with the computing power to access it, such as universities. In 1989, Tim Berners-Lee created the world wide web, revolutionizing how people used the internet. In the 1990s, dial-up internet was introduced, and internet service providers (ISPs) started providing connections to individual households. The popularity of internet access led to the creation and introduction of broadband in the early 2000s, which has since replaced dial-up. It allowed for much faster internet speeds but was very expensive. This led to low initial penetration rates– just 9 per cent of UK households by 2001, for example. This period also saw the growth of online businesses and the beginning of online entertainment: social media, such as Facebook emerged in 2004, followed closely by YouTube and Reddit in 2005 (Beckett, 2022).

The increasing demand for internet data triggered the introduction of fibre-optic broadband around 2008. This allowed for faster speeds of around 50Mbps – roughly double what was offered with standard broadband.[2] The late 2000s also saw the emergence of 3G and mobile phones. Since people could access the internet virtually anywhere, the 2010s were characterized by a streaming, social media, and speed boom with the greatest broadband penetration rates. Finally, the 2020s have shown that working from home is now possible thanks to broadband, especially with the emergence of 5G and the potential for a fully fibre-based future (Beckett, 2022). Therefore, there is no question that broadband significantly changed our lives, and how

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[1] This report was undertaken by the Centre for the Study of Living Standards (CSLS). The research was conducted by Atakan Bakistan (atakan.bakiskan@csls.ca) and Sarah El Kaissi (sarah.elkaissi@mail.utoronto.ca) under the supervision of CSLS Executive Director Andrew Sharpe and CSLS Deputy Executive Director Timothy Sargent. We would like to thank TELUS for funding the project, and Joe Roswell of TELUS for his insightful and useful comments. We would also like to thank the technical advisory board for the insightful feedback that greatly improved the report. A list of the members of the advisory committee can be found in Appendix C.

[2] Standard broadband was 25Mbps.

businesses operate, yet there is no consensus on the exact impacts on productivity and economic growth.

This survey paper contributes to the literature with a comprehensive and up-to-date analysis of econometric studies on the impact of broadband on productivity, output, employment, and consumer surplus. The literature review includes 55 different quantitative economic papers and a detailed explanation of their data choices, methodology, main findings, and measure of broadband. The review has a section discussing the endogeneity arising from the reverse causality between broadband and economic outcomes. Moreover, we discuss the potential issues in using broadband availability as an instrument for broadband adoption and a brief critique of the simultaneous equation model developed by Röller and Waverman (2001) that is often adapted to understand the causal impact of broadband on output. Finally, the review has a section on the impacts of broadband on other economic outcomes, such as consumer surplus, a discussion on the definitions and measurements for broadband, a summary of broadband-enabled applications, and the mechanisms through which broadband can impact economic outcomes.

The literature review consists of nine sections: 1) key concepts, 2) impact of broadband on output and labour productivity, 3) impact of broadband on total factor productivity, 4) impact of broadband applications on employment, 5) impact of broadband on economic outcomes, 6) impact of broadband on other economic outcomes, 7) methodological issues in estimating the impact of broadband, 8) data limitations in estimating the impact of broadband and 9) conclusion. The sections on employment and other economic outcomes are less detailed as the study focuses on understanding broadband's impact on productivity and output.

I. Key Concepts

A. Definitions and Measurement

Broadband is the transmission of wide bandwidth data over a high-speed and high-quality internet connection. There are six types of leading broadband transmission technologies: 1) Digital Subscriber Line (DSL), 2) Cable Modem, 3) Fibre, 4) Mobile Wireless and Fixed Wireless, 5) Satellite, and 6) Broadband over Powerlines (BPL). Throughout this survey, the term broadband generally refers to total (fixed + mobile) broadband unless specified. DSL is a wireline transmission that uses copper telephone lines to transmit data at high speeds. There are two main DSL technologies: 1) Asymmetric DSL (ADSL), used primarily by residential consumers, and 2) Very high data rate DSL (VDSL), which is offered to businesses (Federal Communications Commission, 2014).

Broadband impacts productivity and economic growth by the degree of penetration and quality. Quality includes speed, reliability, latency,[3] and coverage.[4] The speed varies considerably between the internet provided by Fibre to The Home (FTTH), Fibre to The Node (FTTN), cable, and ADSL. Generally, the speed order from fastest to slowest goes as follows: FTTH > FTTN > Cable > ADSL.

According to the definition set by Federal Communications Commission (FCC) in 2015, broadband is any internet service with a minimum 25 Mbps download speed and a minimum 3Mbps upload speed (U.S. Department of Commerce, n.d.). However, there are efforts by the current FCC Chair Jessica Rosenworcel to change the definition and raise the minimum download speed to 100 Mbps and the minimum upload speed to 20 Mbps. For Canada, according to the Canadian Radio-television and Telecommunications Commission (n.d.), the broadband standards are a minimum of 50 Mbps for download speed and 10 Mbps for upload speed.

On the other hand, according to the International Telecommunication Union (2010), the minimum requirement for fixed broadband is 256 Kbps download speed. The fixed broadband subscriptions include “cable modem, DSL, FTTH/FTTB,[5] other fixed (wired)-broadband

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[3] The time it takes for data to travel from user’s device to a server and back.
[4] How many areas or locations within a region are serviced by broadband infrastructure, regardless of whether or not individuals or households in those areas have adopted the service.
[5] Fibre to the Building.

subscriptions, satellite broadband, and terrestrial fixed wireless broadband." Similarly, the OECD (2019) defines broadband access as technologies providing access to the internet at download speeds of a minimum of 256 Kbps.

There is no consensus on the definition of broadband; the discrepancy between the minimum download speed of 256 Kbps and 25 Mbps is notable with the former being one-hundredth of the latter. The OECD (2021) states one reason that OECD countries did not agree to raise the threshold speed in 2012 is that some countries have the current definition incorporated into legal instruments. Thus, changing the definition would have had "implications for the universal services framework in those countries" (OECD, 2021).

The 25Mbps download and 3Mbps upload speeds are not required for many broadband-enabled applications. However, this is different for 256 Kbps download speed, a minimum speed definition of broadband embraced by ITU, OECD, and most econometric studies. The Broadband Speed Guide by the FCC (2022a) provides the information in Table 1 that associates broadband activities with their minimum download speed. The speeds in Table 1 assume that one activity is running at a time. Higher speeds will be needed if more than one person runs the activity. Table 2 describes the broadband activities and speeds needed to run them for more than one user (FCC, 2022b). Community institutions with multiple users generally need a much higher speed than those in Table 1 (see Table B1).

Table 1: Broadband Activity and Minimum Download Speed (Mbps)

Activity	Minimum Download Speed (Mbps)
General Browsing and Email	1
Streaming Online Radio	Less than 0.5
VoIP Calls	Less than 0.5
Student	5 to 25
Telecommuting	5 to 25
File Downloading	10
Social Media	1
Streaming Standard Definition Video	3 to 4
Streaming High Definition (HD) Video	5 to 8
Streaming Ultra HD 4K Video	25
Standard Personal Video Call	1
HD Personal Video Call	1.5
HD Video Teleconferencing	6

Game Console Connecting to the internet	3
Online Multiplayer	4

Source: Federal Communications Commission (2022a)

Table 2: Broadband Activity, Minimum Download Speed (Mbps) for Multiple Users

	Light Use (Basic functions: e-mail, browsing basic video, VoIP, internet radio)	**Moderate Use** (Basic functions plus one high-demand application: streaming HD video, multiparty video conferencing, online gaming, telecommuting)	**High Use** (Basic functions plus more than one high-demand application running at the same time)
1 user on 1 device	Basic	Basic	Medium
2 users or devices at a time	Basic	Medium	Medium/Advanced
3 users or devices at a time	Medium	Medium	Advanced
4 users or devices at a time	Medium	Advanced	Advanced
Basic Service = 3 to 8 Mbps Medium Service = 12 to 25 Mbps Advanced Service = More than 25 Mbps			

Source: Federal Communications Commission (2022b)

Most of the literature surveyed here focuses on measuring broadband adoption, quality, or investment. To measure adoption, authors tend to focus on the number of broadband lines per 100 inhabitants using either total broadband, only fixed, or only mobile. Alternatively, studies focus on the use of various broadband connections by firms, specifying the technology (DSL, cable, fibre, ultra-fast, etc.). The most common measure of quality used is broadband speed, using data such as the number of connections above a certain speed, mobile broadband speed, and average download speed.

B. Applications of Broadband

It is not broadband itself that has productivity implications; it is the applications, such as e-mail, video streaming, and telehealth.[6] Most studies use broadband penetration rate[7] and speed data to relate productivity to broadband. There are limitations to this approach because the productivity

[6] Broadband can provide health care services through telehealth. The mobile health market - the provision of health services enabled by mobile communications - is expected to reach $102 billion globally by 2022, according to Zion Market Research (2016).
[7] Typically, this refers to broadband subscriptions per 100 people, which acts as a reasonable proxy for broadband uptake by firms.

implications of broadband applications are solely attributed to broadband adoption/availability. The broadband penetration rate data does not specify which broadband applications are used. Therefore, an increase in productivity due to an increase in broadband penetration rate might overestimate the positive effect of broadband access, as some of that effect may be due to a new broadband application that is unobservable in data.

Broadband speed is a prerequisite for applications; therefore, one should expect a high correlation between new applications and speed. Studies that isolate the economic impacts of broadband speed can indirectly address the benefits of broadband applications. The speed data may serve as a good proxy since applications such as YouTube, Zoom, and Facebook could not emerge if not for advancements in broadband speed.

The Australian Government (2018) compiled Table 3 to summarize the impact of broadband applications on various industries. It shows how certain firms may use broadband technologies to improve their productivity. One example is cloud computing, which allows firms to use computing services over "the cloud." Such services include storage, analytics, databases, and networking. Many organizations are turning towards cloud computing due to its lower IT costs, speed, global scale, and reliability (Microsoft Azure, n.d.).

Table 3: Impact of Broadband Applications by Industry

Industry	**Potential 5G benefits and use cases**
Information, media & telecommunications	Supporting the Internet of Things Increasing network capacity Providing access to a fully wireless and mobile internet
Arts & entertainment	Improved user experience with higher-quality videos Mobile broadband in crowded areas that addresses issues with interference and reliability High quality of service despite challenging network conditions
Education	Remote learning and teaching Easier learning for students with special needs
Wholesale & retail	Improved asset tracking experience More interaction with consumers in a dynamic fashion E-commerce, faster mobile payment
Finance & Insurance	Managing larger volume of data, better analytics to address fraud detection and customer segmentation Faster transactions
Professional, scientific & research services	Cloud computing, creation of new software More outsourcing of business service functions

Public administration	Supporting fast-response emergency services Changes to systematic behaviours, easier processes
Health care and social	Internet of medical things Health data mining and analytics Predictive modelling to better anticipate risks to patients Connected medicine to get better quality care

Source: Australian Government (2018)

The OECD (2008) highlights the potential impacts of broadband on innovation in R&D in Table 4.

Table 4: Impacts of Broadband on Innovation in R&D

Examples of the Potential Impacts of Broadband on Innovation in R&D
Enable instant sharing of knowledge and ideas
Lower barriers to product and process innovation via faster and less expensive communications
Accelerate start-ups
Improve business collaboration
Enable small businesses to expand their R&D and collaborate in larger R&D consortia
Reduce time from idea to final product
Foster greater networking
Promote "user-led innovation"

Source: OECD (2008)

Healthcare applications and corresponding qualities varying by speed are emphasized in Table 5 using information from Ericsson (2013).

Table 5: Healthcare Applications and Broadband Speed

		Broadband speed			
Application	**Application Technology**	**1 Mbps**	**10 Mbps**	**100 Mbps**	**1 Gbps**
High-quality, non-real-time video imaging for diagnosis	File transfer	High quality	High quality	High quality	High quality
Cardiology, neurology, and emergency room consultations	H.323 video	Low/medium quality	High quality	High quality	High quality
Cineo-angiography and echocardiograms	H.323 video	Low/medium quality	High quality	High quality	High quality
3D interactive brain imaging	SGI Vizserver	Unsupportable	Unsupportable	Medium quality	High quality
Clinical decision support systems	Web browsing	High quality	High quality	High quality	High quality
Advanced clinical decision support system	Image transfer	Unsupportable	Unsupportable	Medium quality	High quality
Professional tele-education	MPEG 1 video	Low quality	Low quality	High quality	High quality

Source: Ericsson (2013)

II. Impact of Broadband on Output and Labour Productivity

The impact of broadband on output comes primarily from higher productivity. Rivlin and Litan (2001) list four ways broadband can enhance productivity. The first is *reducing the transaction costs* necessary to produce and distribute existing goods and services. The Australian Government (2018) argues that broadband will allow businesses to access information much faster than older technologies, increasing production efficiency. Broadband will also enable new goods and services to enter the market which can impact productivity. For example, using autonomous vehicles enabled by broadband can be more efficient than the existing transportation infrastructure if autonomous vehicles can navigate to remove congestion better than non-autonomous vehicles.

The second way broadband can increase productivity is through *increasing management efficiency*. Firms will be able to optimize their supply chains better and communicate more efficiently both within the firm and with clients. The third is *effective marketing and pricing*. Firms with broadband access can optimize their marketing and pricing strategy by collecting data from customers and competitors. Broadband revolutionizes the print, movie, music, gaming, and advertising industries as clients can reach digital content through high-speed download, reducing transaction costs for both customer and producer, while high-quality video conferences can reduce the number of business trips, which can help reduce firm expenses (Ezell et al, 2009).

The fourth is through *increased competition*. As broadband makes information more accessible, the informational asymmetry in the market is reduced, and prices become more transparent. For example, farmers can source materials at a lower cost through online price discovery, and there will be an improved bargaining position by removing the informational asymmetry barrier (LoPiccalo, 2021). This brings more buyers and sellers to the market and increases the competition. Jensen (2007) shows how having a mobile broadband connection provides fisherman in South India more bargaining power when pricing their fish in local markets. Using a differences-in-differences analysis, the author shows that as more regions gain mobile phone access, the price dispersion of fish across markets decreases.

In this section, we look at studies that look at either economic growth overall or labour productivity (typically measured as GDP per worker or per hour). There is an in-depth discussion on the data employed, the measure of broadband, the methodology, and the main findings for every study. Studies are categorized according to whether the study is conducted across countries, within a country, or at the firm-level. The cross-country studies are divided into those focusing on early datasets (generally those terminating before 2010) followed by those using newer datasets. Appendix tables B1 and B2 provide concise summaries of all the studies discussed in this section.

A. Cross-country Studies

i) Studies on Earlier Datasets

In a cross-country analysis, Czernich et al. (2011) estimate the effect of broadband infrastructure on economic growth for 25 OECD countries from 1996 to 2007. They use fixed-line voice telephony and cable TV pre-existing networks as instruments for broadband and find that a 10 percentage point increase in broadband penetration raises annual per capita GDP growth by 0.9-1.5 percentage points per annum relative to no change in broadband penetration.[8]

Qiang et al. (2009) employ an endogenous growth model based on Barro (1991) to analyze the impact of broadband penetration on economic growth. The authors use data based on 120 countries, of which most are classified as developing. Their cross-country analysis makes it possible to distinguish the effects of growth on developing and developed countries. For developed countries, the authors find that a 10 percentage point increase in fixed broadband penetration between 1980 and 2006 is associated with a 1.2 percentage point increase in annual per capita GDP.[9] This is highly significant given that developed countries experienced an overall average growth rate of only 2.1 per cent between 1980-2006. For developing countries, the magnitude is similar but slightly higher; an increase of 10 additional fixed broadband subscribers per 100 people between 1980 and 2006 is associated with a 1.4 percentage point increase in annual per capita GDP growth during the same period. The authors note that the results for developing countries are statistically significant at the 10 per cent level while results for

[8] The authors give the following example of Germany. In 2003, Germany had a broadband penetration rate roughly 10 percentage points lower than leading OECD countries. Suppose Germany had increased broadband penetration by 10 percentage points in 2003, then their GDP per capita would be 3.6-5.9 percentage points higher in 2007.

[9] This is a change in the growth rate - if the growth rate of GDP per capita was 2 per cent before the increase, it would become 3.2 per cent annually after the change.

developed countries are significant at 5 per cent. They argue this is due to broadband penetration in developing countries not yet reaching critical mass[10] to generate robust aggregate effects.

Zaballos and López-Rivas (2012) focus on Latin American and Caribbean countries in their analysis of broadband. They analyze the impact of broadband on GDP per capita using a non-linear model. Rather than using a production function approach where output is modelled as a function of capital and labour, GDP is modelled as a function of expenditure components: investment, consumption, public spending, and trade balance. To address a possible multicollinearity problem, five significant independent variables are chosen that are thought to impact GDP: 1) interest rate spread, 2) interest on new debt, 3) multilateral debt, 4) net official development aid and 5) fixed broadband penetration per 100 inhabitants. They find that a 10 percentage point increase in broadband penetration in 2005 increases GDP per capita by 3.2 percentage points by 2009. Thus, broadband increases annual per capita GDP growth by 0.8 percentage points averaged over 2005-2009.

Like Zaballos and López-Rivas (2012), Bojnec and Fertö (2012) specify a model where GDP is not a function of labour and capital, using data from 34 OECD countries from 1998 to 2009. Their econometric specification models GDP as depending on investment, government expenditure, inflation, labour productivity growth, trade openness, foreign direct investment, and broadband availability. However, their overall results suggest no significant and positive relationship between broadband availability per inhabitant and per capita GDP growth.

One potential problem with these studies is the potential endogeneity of broadband with respect to economic growth. Arvin and Pradhan (2014) analyze broadband's impact on economic growth for developed and developing countries by examining the Granger causality relationships between broadband penetration and economic growth in 19 countries from 1998-2011. They conduct a panel cointegration test[11] and a Granger causality test.[12] They find that for developed countries, broadband penetration increases economic growth, but growth also increases broadband penetration. For developing countries broadband penetration does not seem to increase growth, but growth does increase broadband penetration.

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[10] Minimum level of participation that allows broadband's positive externalities to show their impact.
[11] The panel cointegration test is used to see whether two times series have a stable, long-run relationship.
[12] Granger causality tests are used to determine whether one time series is useful in forecasting another.

Similarly, Lam and Shiu (2010) conducted a Granger causality study of 105 countries between 2002-2006 to investigate the relationships between teledensity (measured as the number of fixed-line and mobile subscribers per 100 people) and GDP. Using a dynamic panel, the authors investigate this for different subgroups of countries: divided by regions (Africa, Americas, Asia and Oceania, and Europe) and by income (high, upper-middle, lower-middle, and low). They find various significant Granger causalities, including that real GDP Granger causes teledensity and vice versa for European and high-income countries, teledensity Granger causes real GDP in Asia and Oceania, and for the rest of the categories, real GDP Granger causes teledensity. These relationships are important to consider as they could help explain the discrepancy of findings in the literature.

These findings suggest that the two studies above that found positive impacts of broadband on GDP may well have overestimated the impacts because they did not account for the partial endogeneity of broadband penetration.

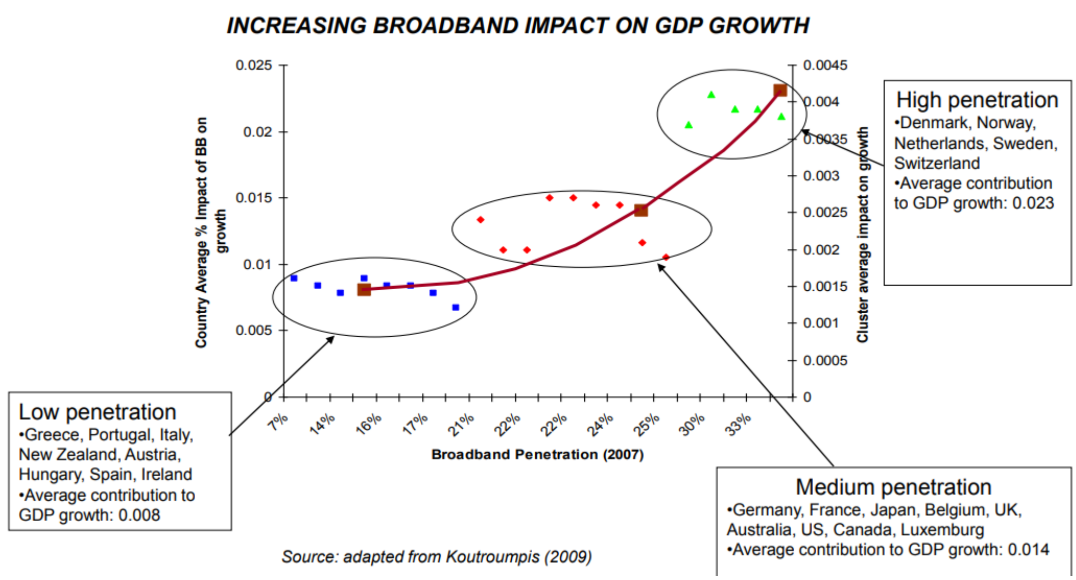
Koutroumpis (2009) uses data from 22 OECD countries from 2002 to 2007 to investigate the link between broadband adoption and economic growth. He deals with the endogeneity issue by using an often-cited simultaneous equation model by Röller and Waverman (2001).[13] The model is based on the joint estimation of a micromodel for broadband investment with a macro production function. Koutroumpis (2009) transforms the equations for demand and supply for telecommunications infrastructure in Röller and Waverman (2001) into demand and supply for broadband infrastructure. The model is based on four equations: 1) aggregate production function, 2) demand for broadband infrastructure, 3) supply of broadband infrastructure and 4) broadband infrastructure production equation. The simultaneous equation approach ensures that the model incorporates feedback between broadband infrastructure and the aggregate economy. Using supply and demand equations endogenizes the broadband infrastructure and addresses the two-way causality of broadband and output. The equations are jointly estimated including country-fixed effects. He finds that a 10 per cent increase in broadband penetration rate generates a 0.25 percentage point increase in the level of GDP growth.[14] For the period studied, this

[13] They find that approximately one-third of OECD Member Country growth between 1970 and 1990 can be attributed to investment in telecommunications.
[14] The author calculates the compounded annual growth effect for Spain to be 0.42% due to broadband penetration increasing from 3.02% in 2002 to 17.70% in 2007.

translates into an average contribution to annual growth of OECD countries of 0.40 per cent per annum.

In addition, the author considers the network externality property of broadband: as the number of broadband users increases, the value of broadband usage increases. Due to network externalities, the impact of broadband penetration on growth will not be linear and can vary across different penetration levels. The author finds that a 10 per cent increase in broadband adoption contributes 0.08 percentage points to annual GDP growth for countries with low broadband penetration (less than 20 per cent), 0.14 percentage points for countries with a medium level of penetration (20 per cent - 30 per cent), and 0.23 percentage points for countries with a high level of penetration (greater than 30 per cent) (see figure 1). Thus, the impact on GDP is non-linear and is highest after a critical mass of 30 per cent of the population with a broadband connection is reached until saturation.

Figure 1: Increasing Returns to Broadband Penetration on GDP growth



Source: ITU (2012)

Finally, Thompson and Garbacz (2011) focus on the different impacts of broadband on low-income and high-income countries while separating the effect of mobile broadband from fixed broadband. The authors use panel data for 43 countries from 2005-2009 and apply fixed-effect IV regressions and include a dummy variable for low-income countries. The results show that mobile broadband is positive and significantly affects GDP high and low-income countries, whereas fixed broadband's effect is insignificant in high-income countries, but negative and significant in low-income countries. In addition, the magnitude of the impact is found to be larger for low-income countries. The authors note that this may be due to near universal service levels of fixed broadband in developed countries, and limited efforts to expand and use fixed telecom investment in developing countries during this period.

ii) More Recent Studies

In an extension of his 2009 paper, Koutroumpis (2019) investigates the impact of broadband speed on GDP for 35 OECD countries between 2002-2016. By adding a quadratic term of broadband speed in the regression, speed is found to have a diminishing impact on GDP. The annual GDP effect from broadband speeds between 2002 and 2016 varies between countries. Mexico, Turkey, Slovakia, and Greece benefited the least with the impact of broadband speed on annual GDP growth is less than 0.08pp. On the other hand, South Korea, Iceland, and Sweden benefited the most, with an annual GDP effect of more than 0.12pp (see Koutroumpis (2019), Figure 1). Overall, the author finds that the OECD region experienced a speed increase of 0.75Mbps in 2002 to 12.85Mbps in 2016, translating into a level increase in GDP of 1.32 per cent – 0.09 per cent annually over the 15 year period.

In contrast, Kongaut and Bohlin (2014) use data for OECD countries from 2008 to 2012 and find that broadband speed positively affects GDP per capita with greater effects for low-income countries. Like many other studies, their model is based on the Cobb-Douglas production function growth model, and they deal with the potential endogeneity problem by instrumenting broadband speed using the percentage of fibre subscriptions of total fixed broadband subscriptions. A comparison between high-income and low-income countries shows that broadband speed has a greater impact on low-income countries, consistent with the results in Qiang et al. (2009). Similarly, Rohman and Bohlin (2012) apply the same approach using broadband penetration, broadband price, and telecom revenue as instruments to estimate broadband speed. They find that doubling the broadband speed in OECD countries increased annual GDP growth by 0.3 percentage points.[15]

Edquist (2022) uses country-level panel data from 116 countries between 2014 and 2019 to estimate the impact of mobile broadband speed on labour productivity measured by GDP per worker. The estimates are generated using fixed effects regression by modelling labour productivity as a function of the capital-labour ratio, human capital, and mobile broadband speed. While the author acknowledges the potential endogeneity, the only attempt to solve it is to lag mobile broadband speed by one year. However, this does not necessarily solve the endogeneity problem because the previous period's productivity will affect the previous period's mobile broadband speed, and the evidence shows that previous productivity is correlated with this period's productivity. Thus, endogeneity remains a problem. He finds that a 10 per cent increase in mobile broadband speed in the previous period is associated with a 0.2 per cent increase in the level of labour productivity.

Edquist et al (2018) use country-level data from 90 countries between 2002 and 2014 to estimate the impact of broadband adoption on GDP. They instrument broadband adoption as the number of mobile broadband subscriptions per 100 inhabitants in 2002 and find that a 10 percentage point increase in broadband penetration increases GDP by 0.1-0.4 percentage points.

Mayer et al. (2019) investigate whether broadband network penetration is a determinant of economic growth using quarterly data for 29 OECD countries from 2008 to 2012. They criticize the model specification of Koutroumpis (2009) and Czernich et al. (2011) due to their static nature and limited treatment of endogeneity. They argue that the change in broadband infrastructure can affect current and future GDP. Therefore, in the regression specification, GDP needs to depend on the explanatory variables' current and past values. Increased broadband penetration and quality will affect future GDP due to learning, reorganization, and innovation (OECD, 2019). This creates a need for autoregressive models. However, the static fixed-effects panel data models ignore the dynamics, and excluding lagged variables creates biased estimates due to omitted variable bias. They find that the coefficient of the broadband penetration rate in the dynamic growth equation is statistically insignificant. They conclude that the

[15] If the GDP growth rate was 2 per cent in 2008, doubling broadband speed would increase the growth rate to 2.3 per cent.

misspecification of the static models in other studies leads them to overstate the economic impact of broadband.

Moreover, Mayer et al. (2019) point out that explanatory variables in the growth model are endogenous, but the only endogeneity addressed in other studies is the potential endogeneity of broadband with respect to output. The threshold model is applied to allow parameters between high-income and low-income countries to vary as it is thought that the impact of broadband on economic growth is translated differently depending on the country's income level (see Qiang et al. (2009)). In contrast to other studies, Mayer et al. (2019) introduce an interaction variable between speed and broadband coverage and find it to be negative, but speed alone is positive. The negative interaction term means that the impact of broadband speed is higher for countries with lower broadband penetration levels. Mayer et al. (2019) also find that the impact of broadband penetration on economic growth is greater for low-income countries than for high-income countries.

B. Within-country Studies

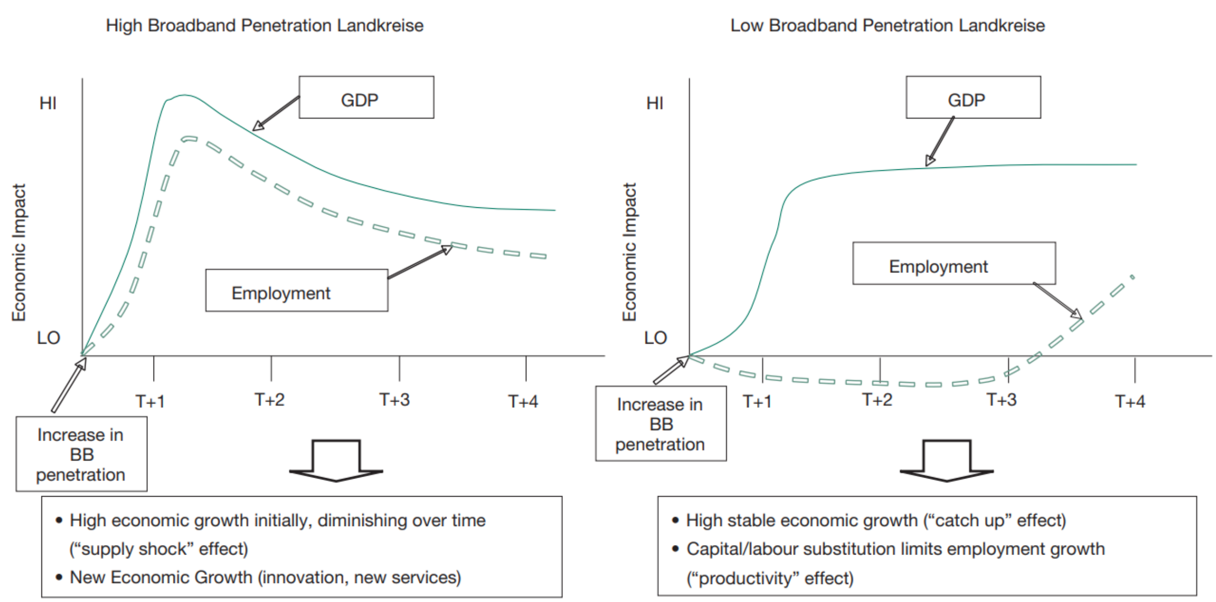
Several studies focused on the impact of broadband on growth using data from only one country. Annual national data will provide an insufficient number of observations given the short period of time over which broadband has been in existence. However, quarterly data or data based on the country's administrative divisions can mitigate this problem (Minges, 2016). Furthermore, the country-level analyses do not consider the heterogeneous impact of broadband on regions of a country. There is no reason to assume that the impact is uniform across all territories of a country.

Jung and López-Bazo (2020) use data from 27 Brazilian states for the period 2007-2011 to analyze the regional impact of broadband on labour productivity. The initial OLS estimation provides biased estimates for the coefficient of broadband infrastructure on labour productivity due to reverse causality - investment in broadband can drive labour productivity but can also be the result of productivity (Cardona et al., 2013). To solve this problem, the authors choose an IV approach using the number of voice-telecommunication fixed access lines per 100 inhabitants with a five-year lag and lagged population density as instruments. Overall, results suggest that the impact of broadband on productivity is positive but not uniform across provinces. Although the impact depended on connection quality and network effects, less developed regions benefited more from broadband.

Crandall et al. (2007) investigate the effect of broadband penetration on output in the United States between 2003-2005. They generate estimates for the entire non-farm private sector and 2-digit sectors such as manufacturing, business, and financial services. The aggregate results suggest there is a positive but non-significant impact of early broadband on GDP. This could be because their study period only covers the early implementation of broadband, and thus it is not possible to measure the full impacts. As for the sector-specific findings, the only significant effects are in the services sector.

Katz et al. (2010) focus on the impact of broadband on the German economy. The authors estimate the total investment required to meet the government's broadband targets and analyze whether the cost is justified by measuring the impact on economic output. They estimate that the required investment will be €36 billion, generating €170 billion of additional GDP - 0.6 per cent of GDP growth in Germany. Figure 2 shows that for regions with high broadband penetration (left), there is a large increase in output growth that diminishes over time, whereas areas with low broadband penetration (right) experience more stable growth (catch-up effect).

Figure 2: Differential Economic Effects by Region



Source: Katz et al (2010)

Time series models at the national level include Katz and Callorda (2013), who use microdata from Ecuadorian household surveys and find that households' average income in cantons that were unserved before 2009 increased by 3.7 per cent annually between 2009-2011 due to broadband deployment. Using the simultaneous equation model initially developed by Röller and Waverman (2001), the authors conclude that every 10 per cent increase in fixed broadband penetration is associated with a 0.5 percentage point increase in average annual GDP growth of between 2008-2012.

C. Firm-level Studies

A study of the introduction of broadband by Bertschek et al. (2013) examines the expansion of DSL's impact on German firms' productivity and innovation activity from 2001 to 2003 using firm-level data from the ZEW ICT survey. The logarithm of sales per employee is used as a measure of labour productivity. Innovation activity is a binary variable taking the value one if an innovation has been realized, and its impact is analyzed using a recursive binary probit model. Initially, the authors estimate the production function framework using OLS and find positive results; however, the optimal choice of inputs (including broadband usage) may be impacted by firm performance, creating an issue of reverse causality which renders OLS estimates biased. Thus, they instrument firms' broadband usage using the regional availability of DSL. They also use control variables such as computerization of workplaces, firms' previous experience with innovation, regional dummies, and GDP per head at the county level. The authors' main conclusion is that broadband had no impact on firms' labour productivity but had a positive effect on firms' innovation activity.

DeStefano et al. (2023) reaffirm the findings of Bertschek et al. (2013) by applying a fuzzy regression discontinuity design using plant- and firm-level panel data in the UK from 2000 to 2004. The geographical discontinuity they exploit arises from a historical accident resulting in firms on one side of a geographical boundary having broadband access and those on the other having no access allowing broadband adoption to be considered exogenous. Sales per worker are used as a measure of labour productivity, as in Bertschek et al. (2013). The authors find broadband use had no effect on firm performance.

Although these studies using early datasets found null effects, some newer literature has found positive effects. Gallardo et al. (2021) argue that the link between productivity and broadband should be analyzed from a more extensive socioeconomic perspective. The authors criticize the previous studies for focusing only on availability or adoption rather than on specific aspects of broadband, such as broadband at different download/upload speeds, digital divide index, and digital distress. Using county-level data in the United States in 2017, Gallardo et al. (2021) employ OLS models with spatial dependence that include ten unique broadband-related variables. Labour productivity is measured as GDP per job and included in the estimation as the dependent variable. The authors find that broadband adoption and digital distress had a more significant impact on job productivity than broadband availability and speed. It is important to note that Gallardo et al. (2021) did not account for the endogeneity between broadband adoption and productivity; thus, their OLS estimates may be biased. This weakens the value of these findings compared to earlier studies, which all attempt to solve the endogeneity issue.

Grimes et al. (2012) use propensity score matching to control for factors that could determine a firm's broadband choice. The data comes from two sources: 1) unit record responses to Statistics New Zealand's Business Operations Survey 2006 and 2) Statistics New Zealand's prototype longitudinal business database (LBD). The extensive nature of data allows the authors to control for numerous factors such as firm size, firm age, industry structure facing the firm, the quality of ICT infrastructure in the firm's locality, being foreign-owned, etc. There are 6,051 firms with detailed characteristics in their merged data, making propensity score matching an attractive methodology. The authors estimate three average treatment effects: 1) broadband vs. no broadband, 2) slow broadband vs. no broadband, and 3) fast broadband vs. slow broadband on the firms' average productivity in 2005 and 2006. Results suggest that the labour productivity effect of switching from no broadband to adopting broadband is a level increase of 10 per cent for the period studied. Finally, no productivity effect is observed for the third average treatment effect. Therefore, switching to fast broadband from any other form of broadband is an insignificant determinant of labour productivity growth.

In addition to looking at the productivity implications of firms having broadband access, one should also investigate whether employees' access to mobile broadband impacts firm productivity because mobile internet access can improve information flows and communication and reduce associated costs. Bertschek and Niebel (2016) is the first micro econometric study that explores the link between firms' labour productivity and the share of employees with mobile internet access. The authors use data from 2143 German firms in 2014 and find that firms' labour productivity (defined as sales per employee) increases as the share of employees with mobile internet grows. The production function is augmented by the share of workers with internet access, with mobile internet access, and predominantly using computers. Both OLS and IV regressions are used to analyze the causal impact of mobile internet access on productivity controlling for firm size and the share of young employees. Two instruments are used: the average mobile internet use at the industry level and the number of years the interviewee owns a smartphone. The IV estimation provides evidence of the positive causal impact of mobile internet use on labour productivity. They find that the share of employees with mobile internet devices is positively correlated with labour productivity.

Summary

In this section, we looked at numerous studies that examined the relationship between broadband penetration and output and labour productivity at various levels (country, region, and firm). Studies of the early implementation of broadband had mixed results, and anyway failed to consider the potential impact of endogeneity on their results. Later studies which include more recent data have generally found a positive association between broadband penetration and output.

III. Impacts of Broadband on Total Factor Productivity

This section reviews studies that investigate the impact of broadband on total factor productivity (TFP). TFP is a measure of all influences on output growth other than the contributions of capital and labour through their private marginal products (Romer, 2019). By focusing on TFP rather than labour productivity or GDP, these studies are trying to identify the broader benefits to the economy (spillover effects) that are not captured by the companies investing in the broadband capital stock. Studies are categorized according to whether the study is conducted across countries, at the firm, or industry level. Appendix tables B3 and B4 provide concise summaries of all the studies discussed in this section.

A. Cross-country Studies

Bartelsman et al. (2019) use cross-country and industry-level data from 10 European countries between 2002-2010 to estimate the impact of broadband on firm TFP. They measure broadband adoption as the proportion of broadband internet-connected employees and obtain estimates using pooled OLS. This is one of few studies that try to disentangle the complementarity between broadband adoption and the innovation process within firms. By including variables to measure the link between TFP and innovations, as well as a variable to measure broadband adoption, the authors can ensure they do not attribute too much of the change in TFP to broadband as opposed to the innovative process in firms. Nevertheless, they find that broadband adoption is more important for determining TFP than the innovative process in firms. They find that a 10 percentage point increase in broadband connected employees increases the level of TFP by 3.6 per cent during the period studied, which is equivalent to an increase of 0.45 percentage points to the growth of annual TFP.

Gal et al. (2019) combine cross-country firm-level data on productivity and industry-level data on digital technology adoption to measure the effect on firm productivity while accounting for firm heterogeneity. They use data from 20 OECD countries between 2010-2015. They measure digital adoption by the share of firms using a specific technology (such as high-speed broadband internet connection or cloud computing) and firm productivity as TFP growth. For high-speed broadband, they find that a 10 percentage point increase in adoption leads to an instantaneous increase in TFP of 1.4 percentage points. After 5 years, the level of TFP would be 5.8 per cent higher. This implies an increase in annual TFP growth of 1.2 percentage points. Furthermore, they find that effects of high-speed broadband are stronger in manufacturing and routine-intensive activities. They note that effects on TFP growth are also stronger for more productive firms and weaker in the presence of skill shortages which provides insights into the complementarities between digital technology and other forms of capital.

B. Firm-level Studies

Haller and Lyons (2015) use DSL broadband availability as an instrument for broadband adoption. Using firm-level panel data from 2002-2009 for 2290 Irish manufacturing firms, the authors use fixed effects and instrumental variables (IV) regression and conclude that the effect of broadband adoption on a firm's TFP is not statistically significant. This finding holds for all types of broadband and higher-speed DSL broadband.

Cambini et al. (2023) use a panel dataset of Italian firms for the 2013-2019 period to measure the impact of firms' adoption of ultra-fast broadband (UFB) on TFP. The authors note that the main issue in production function estimation is the endogeneity of inputs since they respond to a firm's productivity level. They therefore opt for a control function approach, which uses a firm's demand for intermediate inputs to instrument for its unobserved productivity level, then estimates the impact on TFP by IV regression using the firm's municipality's distance from the closest backbone node as the instrument for broadband adoption. They estimate that that UFB adoption increased the level of TFP by 2.9 per cent over the period 2013–2019, which is equivalent to an increase in annual TFP growth of 0.48 percentage points.

Dalgic and Fazlioglu (2020) find that switching from standard broadband to fast broadband plays a significant role in improving firms' TFP. These findings are based on Turkish firms from 2012-2015. They find that firms that switch from normal broadband to faster broadband have a TFP that is initially 5.3 percentage points higher than firms that do not switch, and TFP that this difference grows to 6.5 percentage points in the following year.

Zhang et al. (2022) exploit the "Broadband China" program which aims to speed up networks, lower service fees and increase coverage in China. 120 cities have been selected for a pilot program, and so it serves as a quasi-natural experiment in which changes in broadband infrastructure can be treated as an exogenous shock to firm productivity. This allows the authors to estimate the impact using differences-in-differences (DID). The authors measure broadband as a binary variable equal to one if the registration place of the firm is in a "Broadband China" pilot city and use TFP as the dependent variable. They conclude that TFP levels increased for pilot city firms by 3.97 per cent, and the increase is more evident in capital-strapped firms, non-state-owned enterprises, and highly capital-intensive firms.

The Australian Government (2023) analyzed the impacts of switching from DSL to fibre or cable broadband using firm-level data between 2009-2019. By focusing on the sample of firms that switch, they were able to estimate the effects of adopting better technologies without running a randomized controlled trial. They find that firms that switch technologies experience an immediate increase in TFP of 4.2 per cent. Furthermore, they find that this difference is observable and sustained over several years.

Giannini et al. (2022) analyze the impact of the digital economy on TFP in Italian firms between 2003-2018. They analyze the relationship between broadband adoption and TFP regionally before and after the financial crisis in 2008. They find overall there is a strong positive relationship between broadband adoption and TFP before 2008, but the relationship was less evident after the crisis indicating a structural change that had different regional impacts. They conclude that the digital economy played an important role as a shock absorber during the recession. Furthermore, policies that focus on digitalization of southern firms will help fill the productivity gap between North and South Italy.

Finally, Fabling and Grimes (2021) also concentrate on the speed factor of broadband and see whether there are TFP gains from UFB adoption. The data is drawn from Statistics New Zealand's Longitudinal Business Database (LBD), which includes survey and administrative data on business practices and performance. In New Zealand, the broadband infrastructure roll-out's primary goal was to provide access to schools. Therefore, firms closer to schools are more likely to access broadband. The proximity to schools is then used as an instrument for broadband usage, and the results are estimated by OLS and IV regression. The authors find that UFB adoption positively impacts TFP, finding that firms that adopt UFB in 2012 increase TFP by 0.38 per cent between 2010-2014. In addition, TFP growth is higher for UFB-adopting firms that make complementary investments.

C. Industry Studies

Nadiri et al. (2018) examine the impact of modern communication infrastructure characterized by high broadband speed on different industries using data from 41 United States industries from 1987–2008. The cost function for each industry is estimated, with cost depending on labour, capital, material, output quantity, the flow of services from telecommunication infrastructure capital (including broadband infrastructure capital), the flow of services from public infrastructure capital, and the broadband penetration rate per 100 inhabitants. By taking a partial derivative of the cost function with respect to broadband penetration, cost savings from a one-unit increase in broadband penetration can be derived. This can later be interpreted as the marginal benefit from broadband interpretation. The non-linear square method estimates the translog cost function with the factor-share and revenue-share equations. Results suggest that the marginal benefit is higher in service industries. The five industries with the highest marginal benefit of broadband penetration are 1) other services, 2) health and social assistance, 3) banking, 4) construction, and 5) retail trade. Furthermore, the authors find that industries have higher TFP when more modern communications infrastructure or broadband is used, but the degree of impact varies between industries.

Duso et al. (2021) find similar industry-specific results in Germany. The authors use firm-level data for 2010-2015 and measure broadband as the proportion of broadband available at 16Mbps transmission speeds lagged by one year. They note that average proportion of broadband available at 16Mbps speeds increased from 17 to 55 per cent during their study period. They find that this increased broadband availability did not change the TFP of manufacturing firms but did have a significant positive effect on service sector firms, with the estimated impact on the level of TFP over the 6-year period ranging from 0.76-6.8 per cent. The largest impact of broadband availability in the service sector is in advertising and market research.

LoPiccalo (2021) focuses on the impact of broadband on agricultural outcomes in the United States using county-level panel datasets for 2007, 2008, 2012, and 2017. The results provide evidence of crop yield improvements (their measure of productivity) from increased broadband penetration. Broadband allows farmers to discover prices online and receive materials at a lower cost. Farmers can access information on weather, commodity markets, and services such as online banking via broadband that would improve their agricultural outcomes. For estimation techniques, both the fixed-effects and IV approaches are used. The instrument is chosen to be the average broadband penetration rates for the same speed threshold in all adjacent counties, thus varying by each county. The authors find that doubling the number of broadband connections per 1,000 households is associated with a level increase of corn yields by 3.8 per cent.

Summary

By and large, the cross-country, firm-level, and industry-level analyses of the impact of broadband on TFP do find a positive impact. This finding is not universal though: one of the firm-level studies finds no impact, while another does not find an impact for manufacturing.

IV. Impact of Broadband on Labour Market Outcomes

Investment in and use of broadband internet can also have impacts on the labour market, which we will examine in this section. Appendix tables C5 and C6 provide concise summaries of all the studies discussed in this section.

As highlighted in the Global Symposium for Regulators (2010) hosted by the International Telecommunication Union (ITU), in the short term, broadband construction *directly* creates new employment, such as telecommunications technicians, construction workers, and civil engineers, throughout the deployment of network facilities. In addition, jobs such as metal product workers, electrical equipment workers, and professional services are *indirectly* created from upstream buying and selling between sectors. Income earned from the new employment translates into household spending, which then *induces* new jobs for retail trade, consumer services, and consumer durables.

New jobs are also created through recent applications enabled by broadband, such as telemedicine, e-commerce, online education, social networks, and cloud computing. It is worth emphasizing that broadband is just an enabler, and the applications will have different employment implications depending on its use.

It should also be noted that, at least in principle, broadband internet could have negative impacts on employment in certain sectors, to the extent that it allows for firms to make efficiencies by reducing their workforce. Whether the employees who lose their jobs find work elsewhere depends on whether broadband can indeed lead to the creation of other jobs in the economy, as well as other factors such as the state of aggregate demand. Several studies used input-output analysis to forecast the employment effect of investment in broadband. For example, Katz et al. (2010) concluded that approximately €36 billion of investment in broadband technology would generate a total of 960,000 jobs in the German economy: 541,000 from the construction of the network and 430,000 from the deployment of the network. The authors estimated that the broadband network construction has a Type 1 multiplier effect[16] of 1.5, meaning that for every broadband job, 1.5 other jobs are created. In addition, the Type 2 multiplier effect[17] is estimated

[16] Type 1 multiplier effect = (Direct Employment + Indirect Employment)/Direct Employment
[17] Type 2 multiplier effect = (Direct Employment + Indirect Employment + Induced Employment)/Direct Employment

to be 1.9. It is unclear from the paper whether these jobs created are permanent or transitory; however, they are likely transitory, especially those generated by the construction of the network.

Most of the studies use multivariate regression to analyze the impact of broadband on employment. Crandall et al. (2007) use state-level data on 48 states in the United States for the period 2003-2005 and choose broadband lines per population as a proxy for broadband penetration. Results suggest that a 10 percentage point increase in broadband penetration in a state leads to an employment increase of 2 to 3 per cent per year. In addition, the effect of broadband penetration on employment in different sectors is investigated, and the authors find that broadband deployment has a significant positive impact on employment in service sectors, such as finance, education, and healthcare.

Kolko (2012) finds that an increase in broadband providers (defined as "providers offering broadband services at 200 kilobits per second or faster") positively affects employment growth. The author finds that as the number of broadband providers increases, technology-intensive sectors benefit much more than other sectors, such as mining and public administration.

The impact of broadband on employment will likely vary by the skill level of the workers. Jobs in industries without broadband connection may only be affected by the spillover effects of adopting broadband by other industries. Atasoy (2013), using 1999-2007 ZIP code and county-level data for the United States, estimates OLS and fixed-effect regression models to find that broadband increases employment for workers with a college degree but decreases employment for those without a college degree. Mack and Faggian (2013) confirm the skill-based technological change of broadband using a spatial lag regression model with a positive interaction term between broadband and workers' education level using United States data between 2000-2007.

Ivus and Boland (2016) is the first study to provide an empirical analysis of the effect of broadband on employment in Canada. Using 1997-2011 municipality-level data, their static IV regressions show that broadband availability increases employment and wage growth in rural areas more than in urban areas, and the impact is more significant in industries with high IT intensity.

Broadband impacts employment not just by the degree of penetration but also by its quality. One proxy for the quality of broadband is the speed. Using data from 496 United States counties from 2011 to 2014, Bai (2017) uses a first-differenced model to investigate the impact of broadband speed on employment. Results suggest that faster broadband did not positively affect employment more than normal-speed broadband.

Instead of using state-level data, some studies preferred more detailed data like ZIP code-level, county-level, municipality-level, and firm-level data. One example of using county-level and municipality-level data is Czernich (2014) where the impact of DSL-based broadband availability on unemployment rates is examined for Germany from 2002-2006. The author finds that DSL availability does not have a statistically significant effect on the unemployment rate.

On the other hand, Jayakar and Park (2013) use county-level data from the United States between 2008-2011. They find that investment in broadband infrastructure reduces unemployment. Their prediction suggests that increasing the national average proportion of households with at least 3 Mbps in download speed by 7 per cent would reduce the unemployment rate by 0.49 percentage points.

Summary

As with the impacts on output, labour productivity and TFP, studies looking at the impact of broadband investment on employment generally find a positive impact on overall employment, although there are exceptions. However, studies that look at the impact by skill level do find that better educated workers are more likely to benefit and that employment for less educated workers can be negatively affected.

V. Impact of Broadband Applications on Economic Outcomes

As noted earlier, it is not the installation of broadband *per se* that affects GDP growth but the applications that are enabled by its use. Other than Bartelsman et al. (2019) the studies discussed thus far have not tried to disentangle the complementarities between broadband and its applications. One application that is thought to improve the productivity of firms is Doodle, which is an online calendar tool helpful for time management and coordinating meetings. This section presents the few studies that investigate the impact of broadband applications on output and productivity. Appendix tables B5 and B6 provide concise summaries of all the studies discussed in this section.

An application that could only exist with broadband is Facebook. To estimate the effect Facebook had on GDP growth in the United States, Brynjolfsson et al. (2018) used a discrete choice experiment in which participants had to choose between keeping Facebook or giving it up for a month and receiving a certain amount of money in return. Using the data collected, they calculated that Facebook increased real GDP growth by 0.11 percentage points on average per year between 2003-2017.

Colombo et al. (2013) focus on the change in productivity performance of small and medium enterprises (SMEs) from broadband adoption by focusing on applications. The authors use firm- and province-level data from a sample of 799 firms observed from 1998 to 2004 in Italy. Initially, the authors group firms by the type of broadband application (basic, such as email or advanced, such as supply chain management systems), then they estimate the production functions using two-step GMM. Their main conclusion is that basic broadband applications do not significantly affect productivity, but advanced applications can have a significant impact under certain conditions. These conditions include the industry in which SMEs operate and whether organizational changes are undertaken. For example, service firms can increase productivity by adopting broadband-enabled applications such as file-sharing systems and software applications that facilitate organizational changes.

Although broadband applications can have positive effects on productivity, studies also show that the use of smartphones can have very negative effects on worker productivity (Zimmerman, 2017). Using a questionnaire with 605 German respondents, Duke and Montag (2017) provides empirical evidence on this issue. The questionnaire asked about smartphone ownership, private and work-related smartphone use in hours per week, smartphone addiction and productivity, and provided respondents individualized feedback on their smartphone addiction score. The authors find that there is a positive relationship between smartphone addiction and a self-reported decrease in productivity due to spending time on the smartphone during work.

Internet of Things & Industry 4.0

One key application of broadband internet that is likely to become more important in the years to come is "Internet of Things" (IoT) - linking machines and objects to digital networks. Edquist et al. (2021) constructed a panel of 82 countries between 2010-2017 to measure the impacts of the Internet of Things (IoT) on TFP growth. Using a first differences technique, they find that a 10pp increase in the number of IoT connections per inhabitant is associated with a 0.23pp growth in TFP,[18] and this relationship is still seen when the panel is divided into OECD and non-OECD countries. Using a growth accounting framework, they estimate that the average IoT contribution to growth will be 0.99 per cent per annum between 2018-2030, which translates to $850 billion per annum in 2018 prices. These estimates are much more conservative than others in the literature (see Baily and Manyika, 2015).

Internet of Things can also potentially impact employment. Using data from 107 countries between 2010-2019, Clemente (2021) estimates the impact of IoT connections per 100 inhabitants on the employment within a country. The author finds that 1 additional IoT connections per 100 inhabitants is associated with an increase in employment of 0.059 per cent in OECD countries. However, the author also notes that the 10-year average number of IoT connections in OECD countries was 12.9, and grew on average by 2.3 connections per year. Thus, the result is economically negligible.

[18] This is not a level change. If TFP was 1 per cent initially, then IoT connections increased by 10 per cent, the new TFP growth rate would be 1.23 per cent.

VI. Other Impacts of Broadband

Although our focus is on the impact of broadband on productivity and economic growth, many studies have focused on more specific impacts, including the impacts on SMEs, human capital, work-from-home productivity, consumer surplus, and education. Furthermore, the discussion of the pandemic is beyond the scope of this literature review, but it was a major driver in the work from home movement, thus we discuss the studies analyzing the impact of working from home on productivity.

A. Small & Medium Enterprises (SMEs)

Nakavachara (2020) analyzes the effect of broadband adoption on micro-sized, small-sized, and medium-sized enterprises using a dataset of approximately 100,000 manufacturing firms in Thailand between 2004-2017. The authors address the potential endogeneity between broadband and TFP by using the proportion of firms in the same group with a broadband connection as an instrument for broadband adoption. The groups are formed as those of the same size, industry, province, and industrial estate group. Estimation results suggest that broadband adoption can increase the TFP of micro-enterprises by 54 per cent, small enterprises by 23 per cent, and medium enterprises by 44 per cent.

Chaudhuri et al. (2018) use unit-level data for the informal manufacturing sector in India, and using quantile treatment regressions, the authors conclude that the average effect of broadband adoption on informal sector enterprise productivity is positive.

B. Human Capital

Mack and Faggian (2013) aim to investigate the link between broadband provision and productivity, with a focus on evaluating the variability in broadband impacts due to differences in the quality of human capital. They use data from 3,046 United States counties between 2000 and 2007. Due to the unavailability of productivity data at the county level, the change in the natural logarithm of earnings is used as a measure of productivity. Such measures for productivity may not be accurate since productivity gains only sometimes result in a positive change in earnings. The authors develop spatial lag and error models to account for spatial structure in the county-level data. They acknowledge that the impact of broadband depends on the quality of human capital stock within counties and find that broadband has a positive effect only when the level of human capital is high.

Other studies, such as Akerman et al. (2015) also examine the skill-related link between broadband and productivity. The authors explore the connection between labour productivity and broadband, focusing on worker's skill levels from firm-level data in Norway between 2000 and 2008. To address the endogeneity of broadband adoption, they use a public program that rolled out broadband access points and is believed to provide exogenous variation of broadband adoption in firms. Their main result is that broadband adoption increases the relative productivity of skilled labour, especially college graduates, and lowers the marginal productivity of unskilled labour. The explanation is based on broadband complementing skilled workers in non-routine tasks and substituting unskilled workers in routine tasks.

C. Working from Home

Broadband allows employees to work from home, which provides a potential channel for broadband to increase productivity. Etheridge et al. (2020) use data from the UK Household Longitudinal Survey and measure self-reported productivity using the following survey question: “Please think about how much work you get done per hour these days. How does that compare to how much you would have got done per hour back in January/February 2020?” to which respondents choose from 5 choices ranging from “I get much more done” to “I get much less done”. They find that, on average, households report increased labour productivity when working from home. However, they observe labour productivity declines for those working lower-paying jobs and for women.

The "Information and Communication for Development" report by the World Bank (2009) gives the case of British Telecommunications in 2004 as an example of how working from home affected productivity. On average, British Telecommunications employees that work from home had a productivity increase of 15–31 per cent (Qiang et al., 2009). Through reduced office costs, British Telecommunications saved more than £60 million.

Barrero et al. (2021) use the Survey of Working Arrangements and Attitudes (SWAA) data and conclude that, during the pandemic, people with better home internet service had higher subjective well-being conditional on certain factors such as employment status and age. In addition, there were earnings-weighted productivity gains from universal access to high-quality home internet service. Broadband enables working from home, potentially making some workers more efficient than working on business premises. When asked the question, "How does your efficiency working from home during the COVID-19 pandemic compared to your efficiency working on business premises before the pandemic?" approximately 40 per cent of the respondents in the surveys collected from August 2020 to May 2021 by Inc-Query and QuestionPro replied as either "much more efficient," "substantially more efficient" or "more efficient." Less than 15 per cent of the respondents replied as either "less efficient," "substantially less efficient," or "much less efficient."

D. Consumer Surplus

Much of the econometric analysis of broadband's impact on the economy is about capturing the effect of broadband on employment, productivity, and economic growth. Less attention has been given to quantifying the impact of broadband on consumer surplus. Consumer surplus is the difference between the willingness to pay for a product and its price. It is not measured by GDP and is difficult to estimate since preferences differ between people. Broadband can increase consumer surplus through two channels: 1) increasing agents' willingness to pay for internet services because the services are better and applications or 2) decrease their price.

Dutz et al. (2012) use a discrete choice demand model and direct survey method to measure the contribution of home broadband to consumer surplus. The demand function is estimated based on data on consumers' internet service choices when facing different prices. The willingness-to-pay and consumer surplus are then inferred from the estimated demand function. Another data source used by Dutz et al. (2012) is a survey that asks consumers their maximum willingness to pay for broadband services. The consumer surplus is then calculated by subtracting the price paid from the willingness to pay. They estimate the net consumer benefits from home broadband in 2008 in the United States to be $32 billion per year. Greenstein and McDevitt (2011) also use a survey to infer consumer surplus. Using the 2002 survey of broadband users from Savage and Waldman (2004), they estimate the cumulative consumer surplus created by broadband to be $4.8-$6.7 billion (approximately 0.05 per cent of GDP) between 1999 and 2006 in the United States. Goolsbee and Klenow (2006) use the time people spend online as an indicator of expenditure on internet-based technologies and estimate the consumer surplus for the United States to be $3,000 in 2015 per median United States resident (5.3 per cent of median income).

Using a different approach, Rosston et al. (2010) estimate a random utility model[19] using data from a nationwide survey administered by Knowledge Networks Inc. in late 2009 and early 2010. They find that a representative household was willing to pay $79 per month for fast and reliable internet service (the average price for fast internet service was $44), $20 per month for more reliable service, and $45 per month for higher speed.

E. Education

Broadband technologies have found another useful application in the field of education, enabling their widespread use in classrooms, and facilitating distance learning during challenging times like the COVID-19 pandemic. Grimes and Townsend (2021) estimated the impacts of a school's ultra-fast broadband (UFB) adoption on their National Standards passing rates in New Zealand between 2012-2016. The New Zealand government funded a public policy program to develop an UFB network, prioritizing connections for hospitals and schools. This allows the authors to carry out a differences-in-differences study of the new fibre broadband network on academic performance by exploiting the timing of broadband availability in schools. They find that fibre broadband does increase students' passing rates on standardized tests by approximately 1 percentage point. Previous attempts to quantify the effects of broadband on school attainment found no significant results; however, as the authors note, the previous studies did not analyze the impacts of UFB networks, which plausibly explains the difference in findings.

[19] A method that tries to model choices of individuals among a discrete set of alternatives.

VII. Methodological Issues in Estimating the Impact of Broadband

A. Discussion on Endogeneity in Measuring the Impact of Broadband

As noted above, there is an endogeneity problem linked to estimating the economic impacts of increased broadband penetration and speed. Higher use of broadband can stimulate economic growth, and higher incomes arising from the economic growth can create more demand for broadband[20] (Jung and López-Bazo, 2020). The issue is reminiscent of the reverse causality between public infrastructure spending and economic growth/productivity. This discussion is beyond the scope of this review, so we refer the reader to Aschauer (1989) for more details.

State intervention in the telecommunication sector is also a source of endogeneity. If state intervention depends on economic conditions, it will be difficult to separate the effect of policies from the effect of broadband diffusion (Czernich et al., 2011). For example, in response to the economic crisis in 2008 and 2009, governments introduced economic stimulus plans that included investments in broadband (OECD, 2008). If not considered, the decline in economic growth from the financial crisis of 2008-09 can affect the estimates of broadband's economic impact by wrongfully associating the decline with broadband penetration. The distorting effect of the financial crisis can be avoided by re-estimating GDP for 2008 and 2009 as if the financial crisis never happened or by introducing a dummy variable that equals one if economic growth is negative (Minges, 2016).

At the firm level, endogeneity can arise if the optimal choice of inputs (including broadband usage) is influenced by the firm performance (Bertschek et al., 2013). In addition, if capital and labour are correlated with unobserved productivity and technology adoption, the OLS estimates will be biased (Akerman et al., 2015).

B. Critique of the Use of Broadband Availability as an Instrument

One way to deal with this endogeneity problem is to use an instrumental variables approach which attempts to isolate the exogenous aspect of the variable of interest. An instrument must be exogenous, correlated with the endogenous variable (relevance), and only affect the dependent variable through its relationship with the endogenous variable (exclusion restriction). Several

[20] The issue of reverse causality also holds for ICT because investment in ICT can drive economic growth but can also be the result of productivity and economic growth (Cardona et al., 2013).

studies utilize instruments derived from broadband infrastructure availability to examine the causal impact of broadband on productivity. These instruments encompass various factors, from proximity to schools to DSL availability at the postal code level.

Testing the instrument's validity is not always feasible unless certain instruments are assumed to be exogenous, while others can be assessed using a Sargan test.[21] However, it is crucial to note that this still hinges on the assumption that some instruments are valid. Broadband infrastructure availability is likely to predict adoption, fulfilling the relevance condition for instruments derived from it. However, if the link between the instrument and endogenous variable is weak, IV estimation may perform even worse than OLS estimation, as discussed in Stock et al. (2002). In such cases, both the estimator and standard errors can be biased.

Another potential problem is that the exogeneity condition is not necessarily fulfilled when using broadband availability as an instrument for broadband adoption. DeStefano et al. (2023) point out that employing broadband availability as an instrument is not ideal, particularly when infrastructure deployment is driven by profit motives, which is predominantly the case in the private telecommunication sector. Suppose infrastructure investments are concentrated in regions with high-growth prospects. In that case, broadband infrastructure availability indicates a firm's productivity based on location, thus correlating with the error term. Lagged values of broadband availability can be utilized as instruments for broadband penetration, however, there is insufficient evidence to suggest that they satisfy the exclusion restriction or exogeneity. Therefore, caution should be exercised when using them.

An alternative approach that is limited in the literature is to measure the impact of broadband on productivity is to consider the pathway through firm innovation. In this way, researchers can identify the type of innovation brought about by installing broadband, such as process or organizational innovation, which are more clearly linked to productivity. This could be a potential path forward to deal with the reverse endogeneity of broadband in future research.

Overall, while instruments derived from broadband infrastructure availability hold the potential for measuring broadband penetration, it is crucial to acknowledge the limitations and challenges

[21] Statistical test used to assess the validity of instruments.

associated with their validity. Further research and consideration of alternative instruments are necessary to improve the accuracy and reliability of broadband penetration measurements.

C. Shortcomings of the Simultaneous Equations Model

Another way of dealing with the endogeneity problem is through a simultaneous equation model. One such model, used for estimating the economic impact of telecommunications was initially proposed by Röller and Waverman (2001). Essentially, they address the reverse causality issue between income and telecommunications by including supply and demand equations for telecommunications infrastructure. The model is adopted by numerous studies including Katz and Callorda (2013), Koutroumpis (2009), and Koutroumpis (2019). Two issues can be identified with the simultaneous equation model: 1) omitted variable bias in the determinants of broadband penetration and 2) lack of dynamics.

For an example of the first problem. we can use the model in Koutroumpis (2009) as an example. The author defines an equation for the demand of broadband where broadband penetration is a function of GDP per capita, broadband price, education spending (as a percentage of GDP), R&D spending (as a percentage of GDP) and the degree of urbanization.

The challenge is that the determinants of broadband penetration in this simultaneous equation model may ignore certain statistically significant variables in explaining broadband demand. Leogrande et al. (2021) investigate the determinants of broadband penetration in Europe and find that broadband penetration is positively associated with knowledge-intensive service exports and an innovation-friendly environment, negatively associated with government procurement of advanced technology products. These variables are not included in Koutroumpis' (2009) demand specification, which will lead to biased estimates.

Other examples of variables that could contribute to broadband demand that are not typically included are found in the study by Zaballos and López-Rivas (2012). They formulate a non-linear multivariate regression model where the dependent variable is the number of fixed broadband subscriptions per 100 inhabitants and find seven independent variables that are all statistically significant in determining broadband penetration. Some of the variables that are not included in Koutroumpis' (2009) specification are: 1) cellular phones per 100 inhabitants, 2) population aged between 15 to 64, 3) the percentage of households with a PC, 4) IP telephony regulations, and 5) time to start a business. The variables are chosen from the four pillars diagram that explains broadband penetration presented by the Inter-American Development Bank (see Zaballos and López-Rivas, 2012). The four pillars are 1) development of public policies and strategic view, 2) development of strategic regulation, 3) infrastructure deployment, and 4) capacity building in the public and the private sector. None of these variables are included in the simultaneous approach taken by various authors, which leads to omitted variables bias (OVB), and renders their estimates biased. This reduces the validity of their studies and could help explain the range of results found in the literature. Typically, studies that deal with omitted variable bias find null results (e.g., Bertschek et al., 2013).

The second issue of the simultaneous equation model is the lack of dynamics. Mayer et al. (2019) discuss in detail the need for dynamics in the formulation of broadband on economic growth/productivity. The change in broadband infrastructure (or penetration) will affect current and future GDP; therefore, lagged values should be included, and omitting them will result in biased estimates. Due to the spillover effect of broadband infrastructure, it will take time for the complete impact of broadband to be realized (Crandall et al., 2007). Mayer et al. (2019) argue that misspecification of the model, such as the static simultaneous equation, overestimates the economic impact of broadband, providing another insight into the discrepancy of findings across studies.

VIII. Data Limitations in Estimating the Impact of Broadband

A. Critique of the Use of Broadband Penetration Rate

There is uncertainty on what the most appropriate measure of broadband is. As mentioned in the applications of the broadband section, it is not the broadband network that has productivity implications but the applications. The available country-level data is on the number of broadband subscribers per capita. Therefore, the broadband penetration rate is usually defined as the number of broadband subscribers per population. Although there exists data on mobile broadband and fixed broadband, the data does not distinguish between firms and households and instead measures broadband usage by the overall population. Productivity is a notion related solely to producers and not households. Broadband usage by firms and households will have different implications; only the firms contribute to productivity.

Nevertheless, in the literature, broadband usage per capita is a proxy for the broadband usage of firms. The use of broadband applications by firms would be a preferred measure for econometric analysis of the importance of broadband for productivity. However, the data exists only on broadband use but not on which broadband applications are used. While analyzing the economic impacts of broadband, we assume that an increase in broadband penetration and speed results in higher use of broadband applications and developments of new applications and therefore impacts productivity. Thus, this measure of broadband usage may be overestimating the contribution of broadband to firms' productivity.

B. Advantages and Disadvantages of Firm-level Data

Unlike studies on employment and consumer surplus, using firm-level data is more common when understanding the impact of broadband on productivity. In the presence of an outside macroeconomic shock, firms do not react homogeneously, which provides good reason to analyze firm-level data, especially since more macro-level data, such as industry-level data, do not capture the heterogeneity in firms. Moreover, only firm-level data can capture factors such as the effect of firm size, age group of employees, and firm dynamism on productivity.

On the other hand, to understand broadband's aggregate labour productivity implications, firm-level data may not necessarily be better than industry-level data, given that factors that affect aggregate labour productivity are at the national level, and the difference in productivity arising from heterogeneity can be offset across industries. Furthermore, firm-level data is not easily accessible, costly, and often missing human capital data. Although both types of data have their benefits and drawbacks, each will provide different, essential insights, and thus it is useful to have a mix of studies using different datasets.

IX. Conclusion

In this literature review, we have offered a comprehensive exploration of the economic impacts of broadband, with a focus on productivity and economic growth. We analyzed 55 different quantitative economic papers, providing a detailed examination of their methodologies, data choices, and main findings. While not all studies find statistically significant impacts, the literature generally supports the conclusion that there are positive impacts of broadband on economic outcomes such as output and productivity. This is particularly true for studies on more recent periods which attempt to control for the potential endogeneity between output and broadband investment. The fact that these more recent studies cover more recent time periods may also be a factor in explaining the more positive results, as the positive economic impacts, particularly the spillover effects, may well take time to have an impact on the overall economy.

For employment, where broadband investment could have negative or positive effects, studies generally find that the creation of new jobs has significantly offset the loss of jobs from the introduction of new products and process driven by the internet. However, there is evidence from the United States that it is better educated workers who have seen their employment increase: less educated workers. This is consistent with the idea that technological change in recent years has been skilled-biased, benefit more educated workers.

There are also other important impacts discussed in the literature including the impacts of broadband on SMEs, human capital, working from home, consumer surplus and education. In general, these impacts are positive: broadband improves the productivity of SMEs, allows employees to work from home, increases consumer surplus, and improves educational attainment. Furthermore, the applications that broadband has helped enable, such as Facebook, have contributed positively to GDP growth.

We also note several challenges in measuring the impact of broadband on economic outcomes. One challenge is the potential simultaneity between output and broadband penetration, which not all studies address. Another is disentangling the complementarities between broadband and its applications, which can lead to overestimating the impact of broadband on its own. There is also a debate about the best level of aggregation to use, with some studies focusing on cross-country analyses, and others delving into firm-level analyses. Problems also arise in methodologies with some studies omitting variables shown to be important in explaining the relationship between broadband and economic outcomes leading to biased results, and models lacking dynamics to understand how changes in broadband infrastructure can impact both current and future GDP. It will be important for future work to deal effectively with these challenges to better understand the economic impacts of broadband.

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Appendix A – Further Details on Download Speeds

Table A1: Baseline Download Speed Requirements for Community Institutions

Institution	Typical Applications	Download Speeds
Hospital	sharing health records performing virtual consultations connecting first responders	1 Gbps+
Library	operating public computer centers mobile hotspot lending enabling maker spaces	100 Mbps - 1 Gbps+
School	sharing educational material online testing accessing databases	100 Mbps - 1 Gbps+
Small Business	managing inventory operating point-of-sale terminals coordinating shipping	50 Mbps+
Home	completing homework streaming video web browsing	25 Mbps+

Source: U.S. Department of Commerce (n.d.)

Appendix B – Summary Tables of Reviewed Studies

Table B1: Master Table of Earlier Period Studies on Output per capita and Labour Productivity

Reference	Country & Period	Measure of Broadband	Indicator used (DV)	Level of Analysis	Methodology	Instrument	Effect	Magnitude	Significance	Maryland SMS	Deals with Endogeneity
Arvin & Pradhan (2014)	G20 countries 1998-2011	Percentage of total population that are broadband users	Percentage change in real GDP per capita	Country	Panel cointegration test Granger causality test	N/A	Granger causality exists both ways depending on development status	Various results - see table 4	5%	3	Y
Bertschek et al (2013)	Germany 2001-03	Broadband usage by firms	Log sales per employee	Firms	IV Regression Recursive Binary probit model	DSL availability at postal code level	None	N/A	None	4	Y
Bojnec & Ferto (2012)	34 OECD countries 1998-2009	Total broadband per 100 inhabitants	GDP growth	Country	IV Regression	Fixed-line voice telephony and cable TV pre-existing networks	None	N/A	None	4	Y
Czernich et al (2011)	25 OECD countries 1996-2007	Number of fixed BB subscribers per 100 inhabitants	GDP per capita	Country	IV Regression	Fixed-line voice telephony and cable TV pre-existing networks	Positive	10pp increase in BB penetration increases GDP per capita growth rate by 0.9-1.5pp annually	1%	4	Y

DeStefano et al (2023)	UK 2000-04	Use of broadband by firms (speeds exceeding 128Kbps)	Firm Sales Labour Productivity	Firms Plant	Fuzzy regression discontinuity	N/A	None	N/A	None	4	N
Grimes et al (2012)	New Zealand 2006	Use of different broadband connections	Average of firm's '05 and '06 labour productivity	Firms	Propensity score matching	N/A	Positive	BB connectivity increases LP by 7-10%	5%	4	N
Koutroumpis (2009)	22 OECD countries 2002-07	Population with a fixed broadband connection per 100 population	GDP GDP per capita	Country	Simultaneous equations model using IV GMM and 3SLS with fixed effects	N/A	Positive	10% increase in BB penetration rate increase GDP growth by 0.23%	1%	4	Y
Lam & Shiu (2010)	105 countries 2002-2006	Number of fixed lines and mobile subscribers per 100 people	GDP	Country	Granger Causality	N/A	Positive	Various significant results, see table 3	1%	4	Y

Qiang et al (2009)	120 countries 1980-2006	Number of fixed BB subscriber per 100 people	GDP per capita growth	Country	Endogenous growth model	N/A	Positive	10pp increase in BB penetration increases GDP per capita growth rate by 1.21pp for developed. 1.38pp for developing	5% (developed) 10% (developing)	3	N
Thompson & Garbacz (2011)	43 countries 2005-09	Fixed broadband lines per household Mobile broadband lines per household	GDP per household	Country	Fixed effects IV regression	N/A	Positive for mobile None for fixed	0.072	1%	4	Y
Zaballos & Lopez-Rivas (2012)	26 Latin American and Caribbean countries 2003-09	Fixed BB penetration per 100 inhabitants	GDP per capita	Country	Non-linear multivariate regression	N/A	Positive	10pp increase in BB penetration increases GDP per capita by 3.19%	1%	3	N

Table B2: Master Table of Recent Period Studies on Output per capita and Labour Productivity

Reference	*Country & Period*	*Measure of Broadband*	*Indicator used (DV)*	*Level of Analysis*	*Methodology*	*Instrument*	*Effect*	*Magnitude*	*Significance*	*Maryland SMS*	*Deals with Endogeneity?*
Bertschek & Niebel (2016)	Germany 2014	Share of employees with mobile internet access	Labour Productivity	Firms	IV regression	Average mobile internet use at industry level Number of years interviewee owns a smartphone	Positive	10pp increase in share of employees with mobile internet access increases LP by 9%	1%	4	Y
Edquist (2022)	116 countries 2014-19	Mobile broadband speed	GDP	Country	Fixed Effects Pooled Regression	N/A	Positive when once lagged	10% increase in mobile BB speed in t-1 increases LP by 0.2% in t	5%	3	N
Edquist et al (2018)	90 countries 2002-14	Percentage of mobile BB connections Mobile penetration rate >= 1% (binary)	GDP	Country	First differences 2SLS Fixed effects	Mobile telephone subscriptions per 100 inhabitants in 2002. Fixed internet subscribers per 100 inhabitants in 2002	Positive	10pp increase in mobile BB adoption leads to level increases GDP by 0.1-0.4pp	1%	4	Y
Gallardo et al (2021)	US 2017	10 broadband indicators	Labour Productivity	County	OLS with spatial dependence	N/A	Positive	Many results - see table 6	1%	2	N

Jung & López-Bazo (2020)	Brazil 2007-12	Number of connections above 512Kbps per 100 inhabitants in the region	Labour Productivity	State	IV regression	Number of voice telecom fixed access lines her 100 inhabitants Lagged population density	Positive	10% increase in BB penetration increases productivity by 0.9% (level)	1%	4	Y
Katz & Callorda (2013)	Ecuador 2008-12	Percentage of individuals connected to fixed broadband	GDP growth	Household	Simultaneous equations model Fixed effects	N/A	Positive	10% increase in BB penetration increases GDP growth by 0.52%	5%	4	N
Kongaut & Bohlin (2014)	OECD countries 2008-12	Broadband speed	GDP per capita	Country	2SLS	Percentage of fiber subscriptions of total fixed broadband subscriptions	Positive	10% increase in BB speed increases GDP per capita by 0.8% (level)	1%	4	Y
Koutroumpis (2019)	35 OECD countries 2002-16	Fixed broadband subscriptions per 100 people Fixed broadband speed in Mbit/s	GDP	Country	Simultaneous equations by 3SLS with fixed effects	N/A	Positive	Increasing speed from 2 to 8Mbps increases GDP by 0.9%	1%	4	Y

Mayer et al (2019)	29 OECD countries 2008-12	Fixed broadband subscribers per 100 inhabitants Actual broadband download speed (Kbps) Number of years since introduction of BB technology	GDP per capita	Country	Dynamic panel with fixed effects using GMM	Lagged first differences of various independent variables	None	N/A	None	4	Y
Rohman & Bohlin (2012)	OECD countries 2008-10	Average achieved downlink speed	GDP growth	Country	2SLS	Penetration rate, broadband price, urban population, density, and telecom revenue	Positive	Doubling BB speed increases GDP by 0.3% (level)	1%	4	Y

Table B3: Master Table of Earlier Period Studies on Total Factor Productivity

Reference	Country & Period	Measure of Broadband	Indicator used (DV)	Level of Analysis	Methodology	Instrument	Effect	Magnitude	Significance	Maryland SMS	Deals with Endogeneity
Akerman et al (2015)	Norway 2000-08	BB subscription rate for stratified random sample of firms	TFP	Firms	Fixed effects Natural experiment	Public program that rolled out BB access points	Positive	10pp increase in BB availability increases TFP by 0.4%	1%	4	Y
Bartelsman et al (2019)	10 European countries 2002-10	Proportion of broadband internet connected employees	TFP	Firms Industry	Pooled OLS	N/A	BB usage is a better indicator of productivity than innovation	10pp increase in BB connected employees increases TFP by 3.6% (level)	1%	2	N
Colombo et al (2013)	Italy 1998-2004	Principal component analyses distinguishing basic and advanced BB applications	TFP	Firms Provincial	Production function approach Two-step system GMM	N/A	None	N/A	None	4	N
Haller & Lyons (2015)	Ireland 2002-09	Use of different broadband connections	TFP TFP growth	Firms	Fixed effects IV regression	Geographical DSL broadband availability	None	N/A	None	4	Y

Nadiri et al (2018)	US 1987-2018	Broadband penetration rate per 100 inhabitants	TFP	Industry	Non-linear least squares	N/A	Positive	Marginal benefit of BB is highest in service sector	Not reported	4	Y

Table B4: Master Table of Recent Period Studies on Total Factor Productivity

Reference	*Country & Period*	*Measure of Broadband*	*Indicator used (DV)*	*Level of Analysis*	*Methodology*	*Instrument*	*Effect*	*Magnitude*	*Significance*	*Maryland SMS*	*Deals with Endogeneity?*
Australian Gov't (2023)	Australia 2009-19	Broadband technology used by firm. Number of firms switching from DSL to fibre	TFP	Firms	Pooled OLS Fixed Effects	N/A	Positive for pooled OLS None for FE	Firms that switch to fibre or cable BB have annual TFP growth 4.2% higher than firms with DSL	5-10%	4	N
Cambini et al (2023)	Italy 2013-19	Adoption of UFB by firms	TFP	Firms	2SLS	Municipality distance from closest backbone node	Positive	UFB adoption increases TFP by 2.9% (level)	5%	4	Y
Chaudhuri et al (2018)	India 2010-11	Use of broadband and its applications by firm (binary)	TFP	Firms	IV Quantile treatment regression	N/A	Positive	Broadband enhances productivity through basic applications	5% for 45th and 60th quintiles	4	Y
Dalgic & Fazlioglu (2020)	Turkey 2012-15	Firm's use of BB	TFP	Firm	Propensity score matching DID	N/A	Positive	Moving from normal to fast broadband increases TFP 5.3pp between 2012-2015	1.	4	N

Duso et al (2021)	Germany 2010-15	Once lagged 16Mbps broadband availability	TFP	Firms Industry	Control function approach	N/A	Positive in services None in manufacturing	BB increase of 38pp increased TFP by 0.76-6.74% in services	1%	4	N
Edquist et al (2021)	82 countries 2010-17	Internet of Things connections per inhabitant Mobile BB connections per inhabitant	TFP growth	Country	Growth accounting First differences	N/A	Positive	10pp increase in IoT connections increases TFP by 0.23pp (level)	5%	2	N
Fabling & Grimes (2021)	New Zealand 2008-18	Use of ultrafast broadband by firms	TFP	Firms	IV regression	Proximity to schools	Positive	Adopting fibre between 2010-2012 increases TFP between 2010-2014	5%	4	Y
Gal et al (2019)	20 OECD countries 22 industries 2010-15	Share of firms using a specific digital tech	TFP growth	Firms Industry	OLS	N/A	Positive	10pp increase in high-speed BB leads to instantaneous increase in TFP of 1.4pp	1%	2	N

Giannini et al (2022)	Italy 2002-18	Percentage of firms using a PC	TFP	Firms	IV Regression	Percentage of employees using internet facilities	Positive	Increasing the percentage of employees using internet facilities increases TFP	10%	4	Y
LoPiccalo (2021)	US 2007,2012 and 2017	Ratio of number of connections at given speed in county over total number of county households	Farm expenses Yield measures	County	Fixed effects IV regression	Average broadband penetration rate for same speed threshold in adjacent counties	Positive	Doubling BB connections increases corn yields by 3.8%	1%	4	Y
Nakavachara (2020)	Thailand 2017	Use of broadband by firms (binary)	TFP	Firms	2SLS	Proportion of firms in the same group with a broadband connection	Positive	BB adoption increases TFP by 54% for micro-enterprises, 23% for small and 44% for medium	1%	4	Y
Zhang et al (2022)	China 2006-18	Whether registration of firm is part of “broadband China” plot city (binary)	TFP	Firms	Diff-in-Diff	N/A	Positive	"BB China" strategy increases TFP by 3.97%	5%	4	Y

Table B5: Master Table of Earlier Period Studies on Other Impacts

Reference	Country & Period	Measure of Broadband	Indicator used (DV)	Level of Analysis	Methodology	Instrument	Effect	Magnitude	Significance	Maryland SMS	Deals with Endogeneity
Atasoy (2013)	US 1999-2007	Ratio of population living in a broadband available are in a county	Employment to population ratio	ZIP Code County	OLS Fixed Effects	N/A	Positive for college educated Negative for those without college degree	Gaining access to BB services in a county increases employment rate by 1.8pp	1%	2	N
Crandall et al (2007)	US 2003-05	Broadband lines per population	GDP (nonfarm private sector)	State	OLS	N/A	None overall Positive for some sectors	10pp increase in BB penetration increases employment by 2-3%	5%	2	N
Czernich (2014)	Germany 2002-2006	DSL-based BB availability	Unemployment rates	Country	IV Regression	Distance from main distribution frame	None	N/A	None	4	Y
Dutz et al (2012)	US 2005-08	Actual prices paid for Internet services Actual types of internet service purchased	Consumer Surplus Willingness-to-pay	Metropolitan statistical area	Discrete choice model	Market values from other geographic markets	BB connections are a strong substitute for dial-up technology	Consumer benefits from BB in 2008 is estimated to be $32bn per year	5%	3	Y

Etheridge et al (2020)	UK 2020	Self-reported response comparing productivity before and after pandemic	Change in labour productivity	Household	Direct Survey	N/A	On average positive. Negative for low-wage and women	-0.29 low earners 0.07 high earners -0.09 women	1% 5% 5%	2	N
Goolsbee & Klenow (2006)	US 2005	Time people spend online	Consumer Surplus	Individual	Demand curve estimation	N/A	Positive	$3000 per median resident	Not reported	3	N
Greenstein & McDevitt (2011)	US 1999-2006	Total internet, BB, and dial-up adopters	Consumer Surplus	Country	Direct Survey	N/A	Positive	$4.8-6.7 billion	Not reported	3	N
Ivus & Boland (2016)	Canada 1998-2011	Deployment rate measured from BB Index	Employment growth Wage growth	Municipal	IV Regression	Variation in elevation within region	Positive in rural areas	Moving from no BB to BB in 1997, employment in service industry in rural areas increase by 1.17pp	10%	4	Y

Katz et al (2010)	Germany 2000-06	Investment in manufacturing, construction, and telecoms	Employment rate	Rural	Input-Output Analysis	N/A	Positive (with multiplier effects)	36bn investment generates 170.6bn additional GDP and 968,000 jobs Type 1 multiplier effect of 1.45 and Type 2 of 1.92	Not reported	3	N
Kolko (2012)	US 1992-2006	Number of BB providers	Change in Employment	ZIP Code County	2SLS	Average slope of terrain in an area	Positive	0.0636	1%	4	Y
Mack & Faggian (2013)	US 2000-07	Number of BB providers in county in 1999 Whether a county had at least one BB provider in 1999	Change in Earnings	County	Spatial lag model Spatial error model	N/A	Positive for highly skilled human capital	Presence of BB rather than quantity is what affects productivity	1%	3	Y
Rosston et al (2010)	US 2003-10	Responses to choice	Willingness-to-pay for reliable service and improved speed	Household	Discrete choice model	N/A	Positive	$79 per month for fast, reliable Internet	Not reported	3	N

Table B6: Master Table of Recent Period Studies on Other Impacts

Reference	***Country & Period***	***Measure of Broadband***	***Indicator used (DV)***	***Level of Analysis***	***Methodology***	***Instrument***	***Effect***	***Magnitude***	***Significance***	***Maryland SMS***	***Deals with Endogeneity?***
Bai (2017)	US 2011-14	Percentage of county population with access to different download speeds	Change in employment rate	ZIP code County	First differences	N/A	None	N/A	None	2	N
Barrero et al (2021)	US 2020	Internet access quality	Work from home efficiency during pandemic relative to office efficiency pre pandemic	Household	Direct Survey	N/A	Positive	40% of respondents reported being more efficient	Not reported	3	N
Brynjolfsson et al (2018)	US 2003-17	Choice between keeping FB and giving it up for one month and getting paid a certain amount	Willingness to accept price for giving up Facebook GDP growth	Individual	Incentive compatible discrete choice experiments Binary logit	N/A	Positively increases GDP growth	Intro of FB increased GDP growth by 1.54pp	Not reported	3	N
Clemente (2021)	107 countries 2010-19	Internet of things connections per 100 inhabitants	Unemployment rate Total employment	Country	Fixed effects Dynamic panel	N/A	Positive corr. in OECD None for unemp.	10 additional IoT connection increases employment by 0.59%	1% for OECD	4	N

Duke & Montag (2017)	Germany 2016	Series of questions to provide a smartphone addiction score	Self-reported work productivity	Country	Direct Survey	N/A	Positive	Positive correlation b/w smartphone addiction and decreases in reported productivity	1%	3	N
Ford (2018)	US 2013-15	Counties with at least 80% coverage of 25Mbps service	Percentage change in number of jobs, total personal income, or total labor earnings	County	Average Treatment effect with Coarsened Exact Matching	N/A	None	-0.30 0.32 -0.11	None are sig	3	Y
Grimes & Townsend (2021)	New Zealand 2012-16	School's UFB adoption	National Standards passing rates	Regional	Diff-in-Diff	N/A	Positive	Adopting fibre BB increases passing rates by 1pp	5%	4	N
Jayakar & Park (2013)	US 2008-11	Percentage of households with at least 3Mbps download speed	Unemployment rate Change in unemployment rate	County	OLS	N/A	Negative	Increasing # of HH with at least 3Mbps in download speed by 7pp reduces unemployment rate by 0.49%	Not reported	2	N

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