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Impact of broadband speed on economic outputs: An empirical study of OECD countries[1]

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Abstract: A number of studies have indicated that higher broadband penetration leads to greater economic impacts. Nevertheless other characteristics of broadband services such as different speeds are becoming more important to determine the economic impacts. This study estimates the relationship between broadband speed and economic outputs. The results show that broadband speed contributes positively to economic outputs such as GDP. The effects of broadband speed are also greater in countries with lower income. The policy recommendation is therefore that countries should focus on and encourage high speed broadband infrastructure and its adoption in their national broadband plans and policies.

Keywords: broadband speed, broadband policy, GDP, OECD.

JEL code: L96.

Introduction

Due to the development of new innovations and technologies broadband services currently require more transmission capacity to work properly and efficiently with new content. Higher quality video content and more complex applications on internet services also require faster broadband speeds. Hence policy-makers have implemented broadband policy to ensure that countries will have high speed broadband infrastructure for both wired and wireless services. At the same time the use of broadband and its applications has been ex-

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panded to other sectors such as education, public services, health care, online shopping, communication and entertainment. According to the EC (2010) fast and ultra-fast internet is one of the eight action areas in the EU Digital Agenda 2020. The EC stated that there is a need for faster internet and to ensure that citizens can access the services they want. Furthermore, not only in the EU, but several developed countries, such as the US, Japan, Korea and Australia, are also concerned about the importance of broadband speed and are launching their national broadband plans. Many countries have national broadband plans that not only aim for higher broadband penetration but also higher broadband speeds, in the belief that greater speed stimulates greater economic impacts and a better quality of life.

Even though there are concerns about broadband speed almost everywhere only a few studies investigate this issue in the academic field, especially in empirical research. In the past a number of studies have analysed the impacts of broadband penetration on various economic prosperities. A number of academic results have indicated that higher broadband penetration leads to greater economic impacts (see Crandall, Lehr, & Litan, 2007; Koutroumpis, 2009; Thompson & Garbacz, 2011). On the other hand there have so far only been a few studies focusing on the effect of higher broadband speed on different economic impacts, compared with the impacts of broadband penetration. A few examples are Forzati and Mattsson (2012), Rohman and Bohlin (2012) and recently Rohman and Bohlin (2013) who attempt to analyse the micro-economic level of household income. Middleton (2013) suggested that it is not only broadband penetration that matters but also other characteristics such as different speed transmission, type of connection, quality of service and service provider. As these characteristics vary across countries broadband connection on its own may not be a good measurement. This study therefore aims to investigate one of these characteristics: the relationship between broadband speed and economic outputs at the macro-economic level. The OECD countries have been selected as a case study since most of these countries have a sufficient level of broadband penetration. Hence the characteristic of broadband service, in this case – broadband speed – is interesting to analyse as to whether it has any effect on economic outputs. Whilst this study may not cover all the characteristics that have an impact on economic outputs it aims to add more knowledge and empirical evidence to the broadband speed studies, which have so far been limited.

To provide a greater understanding of the possible benefits of high speed broadband Section 1 describes the background to broadband speed in more detail, including its benefits and its relation to the national broadband plan. Section 2 shows the relevant studies that have been conducted since the early 80s. Section 3 explains the research method and data set used in this paper, whilst the empirical results are presented and explained in Section 4. The discussion of the results and their implications are given in the conclusion at the end of the paper.

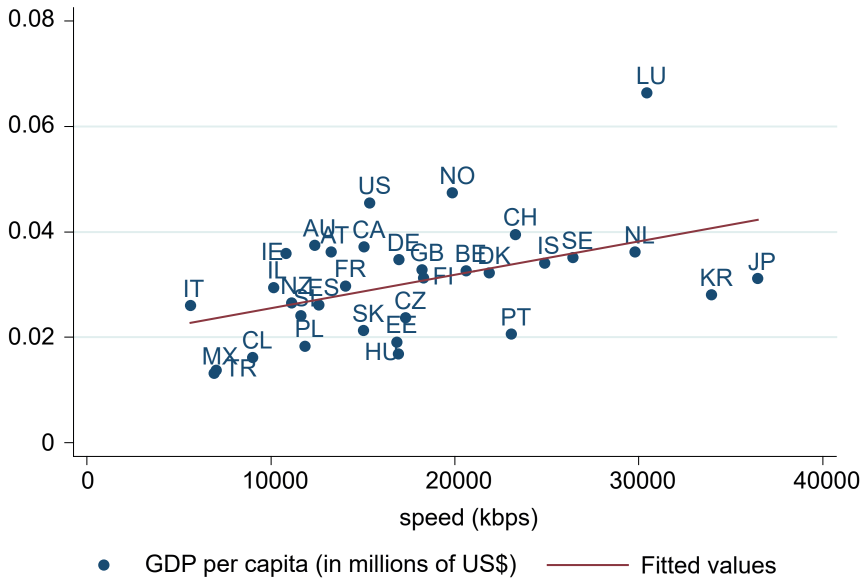
1. Broadband speed overview

1.1. Benefit of greater broadband speed

The use of video websites such as YouTube, Netflix and other streaming video online websites has greatly increased in the past few years. The greater the quality of the video, the higher the broadband speed that is needed, not only for entertainment purposes, but it is also increasingly believed that video communication will provide several benefits in the future. For example, the use of voice over Internet protocol (VOIP), video conferencing, online education and telehealth all need a higher speed capacity to work efficiently. Atkinson, Castro, Ezell, & Ou (2009) explained that faster broadband services from the next generation broadband[4] can significantly improve four main functionalities of internet services compared with traditional broadband: 1) significantly faster file transfers, both sending and receiving, 2) enabling video streaming applications, 3) high quality, real-time communication and 4) enabling users to use many applications at the same time.

Furthermore some scholars have suggested that higher broadband speeds create more employment and stimulate better economic growth (see Katz, Vaterlaus, Zenhäusern, & Suter, 2010; Rohman, & Bohlin, 2012). This is not only limited to the ICT sector as high speed broadband also contributes to the improvement of other sectors and businesses, from medication and education to entertainment. ITU (2012) has concluded that broadband development may benefit an economy in four ways: 1) direct job and action creation through the broadband development project, which works in the same way as in any infrastructure project, 2) the externalities at both business and household level lead to productivity gains in firms and higher household incomes in its residential adoption which ultimately contributes to economic growth, 3) benefits in the form of consumer surplus when consumers pay for the service below the level of their willingness to pay and 4) benefits through other sectors such as access to public, entertainment, education, health care and banking services. Similarly a higher speed of transmission of broadband services is likely to stimulate greater and more efficient effects in addition to these four possibilities. These effects are clearer in the second and fourth categories. For instance with the use of video content from ultra-fast broadband the development of education and health information can become faster and more efficient whilst the business sector can lower its travel costs with video conferencing. Higher broadband speeds can have indirect effects on contents and applications. It is therefore likely that there will be more development of new content and appli-

[4] Next generation broadband generally referred to broadband services from the next generation network (NGN) which can provide fast and ultra-fast internet services. Next generation broadband can be from both fixed and mobile networks; however, most of the time it refers to fast internet from fixed networks.



Relationship between (average) speed and GDP per capita in OECD countries (Q4 2012)

The data for broadband speed are taken from Ookla and the GDP per capita from OECD statistics

cations, which ultimately creates more businesses and employment. To illustrate the benefits of broadband speed and economic output the relationship between one of economic outputs (GDP per capita) and average broadband speed in OECD countries is presented in Figure. Figure shows that in the OECD countries those with a higher average broadband speed generally have a higher GDP per capita than those with a lower average broadband speed. Nevertheless the analysis will be investigated further in later sections of this paper as many factors contribute to GDP per capita, not only broadband speed.

1.2. Broadband speed and the national broadband plan

There has been almost universal recognition of the benefits of broadband services; national broadband plans have therefore been considered important keys to developing the economies and societies of countries further since the mid-2000s (OECD, 2011). In recent national broadband plans broadband speed has started to become more recognised by the authorities and included in the targets of national broadband plans in several countries. The targets, however, vary and are dependent on the development of broadband infrastructure in different countries. Several countries and regions have considered broadband speed as one of their goals (as shown in Table 1). The policy to reach targets of both penetration and speed could vary depending on culture, economics and

Table 1. Broadband targets (speed and penetration) in selected OECD countries

Country	Date of policy	Target			Comment
		Speed	Penetration	Date	
EU	May 2010	100% for 30 Mbps and 50% for 100 Mbps		by 2020	source[a]
UK	February 2013	100% for 2 Mbps and 90% for 24 Mbps		by 2015	source[b]
Sweden	November 2009	100 Mbps	40% in 2015 and 90% in 2020		source[c]
France	November 2011	high speed broadband	70% by 2020 and 100% by 2025		source[d]
Italy	late 2008 (integrated with the EU plan in 2010)	at least 50% for 100 Mbps		by 2020	source[e]
Spain	July 2010	80% for 10 Mbps and 50% for 100 Mbps		by 2015	source[f]
Germany	February 2009	50 Mbps	75% by 2014 and 100% as soon as possible		source[g]
US	April 2009	100 Mbps for at least 100 million households		over the next decade	source[h]
Japan	May 2010	more than 100 Mbps	100%	by 2015	source[i]
Australia	June 2013 (update from May 2011 version)	fibre can provide up to 1 Gbps, wireless or satellite can provide up to 25 Mbps	100% by 2020 (93% connected to fibre in the next 10 years, 7% connected to fixed wireless or satellite in 2015)		source[j]

[a] The European Commission. 2010. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:0245: FIN:EN:PDF.
[b] Department for Culture, Media and Sport. 2013. https://www.gov.uk/government/policies/transforming-uk-broadband.
[c] Ministry of Enterprise, Energy and Communications. 2009. http://www.government.se/content/1/c6/13/49/80/ 112394be.pdf.
[d] Ministry of Economy and Finance. 2011. http://www.ladocumentationfrancaise.fr/var/storage/rapports-publics/114000700/0000.pdf.
[e] Ministry of Economic Development. http://www.sviluppoeconomico.gov.it/images/stories/pdf_upload/DIGITAL-ITALY.pdf.
[f] Ministry of Industry, Tourism and Trade. https://www.planavanza.es/InformacionGeneral/Estrategia2011/ Documents/Estrategia_2011–2015_PA2.pdf.
[g] Ministry of Economics and Technology. 2009. http://www.zukunft-breitband.de/DE/breitbandstrategie, did=523872.html.
[h] FCC. Retrieved 19 July 2013. http://www.broadband.gov/plan/executive-summary/.
[i] Sugaya, M. 2012. Regulation and competition in the JP broadband market. Presentation of the proceeding of the 34th Pacific Telecommunications Council (PTC) Conference, 14–18 January 2012, Honolulu.
[j] Department of Broadband, Communications, and Digital Economy. 2013. http://www.nbn.gov.au/files/2011/06/ Advancing-Australia-as-a-Digital-Economy-BOOK-WEB.pdf.

Source: Compiled by the authors from various sources.

political factors in the countries. Several developed countries are already concerned with the importance of higher broadband speed. In academic works, however, the empirical analysis of the impact on broadband speed is still limited. Since the transmission speed has been taken into account more in a practical world it is also important in academia to understand and point out the importance of the impacts of broadband speed on economic growth, especially in empirical studies, as the data become more available.

To improve the understanding of the impacts of broadband speed on economic growth previous literature on the empirical work on the impacts of ICT on economic growth with the emphasis on the broadband services is discussed in the next section.

2. Literature review

Studies on the impacts of telecommunications infrastructure and services on economic growth have been conducted several times in the past few decades. One of the earlier studies is Hardy (1980). The author used cross-sectional time series data for 60 countries and found that telephones can contribute to economic development. Later more research was conducted on different ICT infrastructures and services. Another interesting study in the 2000s is Röller and Waverman (2001). The authors applied a simultaneous approach to investigate how ICT infrastructure affects economic growth. In fact the authors found a causal relationship between ICT infrastructure and GDP. More importantly this simultaneous approach has since been applied to the case of broadband penetration in Koutroumpis (2009) and mobile telecommunication diffusion in Gruber and Koutroumpis (2011). In Koutroumpis (2009) the author suggested that higher broadband adoption and use significantly increase economic outputs. The effects are also higher in countries with higher penetration such as the Scandinavian countries. In a similar way Gruber and Koutroumpis (2011) found that mobile diffusion has significant positive impacts on economic growth. The impacts are also greater in countries with higher mobile penetration. There are also a number of studies on broadband infrastructure and services from the 2000s and 2010s.

Besides the simultaneous approach in previous sub-sections there are several studies that aim to identify the impact of broadband on economic growth with different methods in the past decade. Lehr, Osorio, Gillett, and Sirbu (2005) estimated the broadband penetration impacts in the US. The authors transformed the economic outputs into a growth variable using control variables to separate the effects of broadband. Their findings support the idea that broadband stimulates economic growth. Rohman and Bohlin (2012) were amongst the first to estimate the impact of broadband speed on economic outputs applying the model by Lehr, Osorio, Gillett, and Sirbu (2005). Whilst the coefficient of broadband speed in their findings was not significant, the square of the coefficient of broadband speed was positively significant. The authors then concluded that doubling the broadband speed contributes 0.3% of GDP growth. Other interesting studies on broadband infrastructure and economic growth in the past few years include Czernich, Falck, Kretschmer, and Woessman (2011) and Thompson Jr. and Garbacz (2011). Czernich, Falck, Kretschmer, and Woessman (2011) applied instrumental variable estimation and found that increasing the broadband penetration rate by 10% stimulates GDP per capita by 0.9–1.5%. Thompson Jr. and Garbacz (2011) divided broadband impacts into direct and indirect impacts. For the direct impacts the authors applied a fixed effect on panel data with adjustments for endogeneity whilst the stochastic frontier production function was used for the indirect impacts.

Nevertheless broadband connectivity on its own cannot fully explain its great impact on economic outputs. Currently the speed and quality of broadband vary across countries. Middleton (2013) mentioned that there are more characteristics to consider for broadband networks such as speed, type of connection, quality of service and service provider. This study may not cover all the characteristics of broadband networks; however it analysed the speed issue, which few studies have done so far. With regard to literature related to broadband speed only a handful of studies have been conducted. Rohman and Bohlin (2012 and 2013) analysed impacts of broadband speed on GDP per capita for a macro-level study and household income in a micro-level study. At macro-level the authors found that doubling the speed in the OECD countries encouraged 0.3% GDP growth compared with the base year. At micro-level the authors suggested that OECD countries can obtain benefits at household level from broadband when the broadband speed capacity is at least in the range of 2–4 Mbps. Furthermore some studies imply that the higher speed contributes to better economic impacts. Katz, Vaterlaus, Zenhäusern, and Suter (2010) analysed the national broadband plan for Germany and suggested that if Germany achieves both the broadband penetration and speed targets there will be more than 960,000 additional jobs and output worth more than 170 billion euro. Forzati and Mattsson (2012) analysed the impacts of job employment from the areas with fibre access. The authors concluded that the increase in the ratio of the population that lives within 353 metres of a fibre-connected premise contributes positively to job employment from 0–0.2% after two and a half years. In recent years there have been more studies related to the contribution of high speed internet. For example Ahlfeldt, Koutroumpis, and Valletti (2015) suggested that the properties with faster internet connection can increase their values compared to those with lower connection. In regard to digital divide study Gijón, Whalley, and Anderson (2016) studied the relationship between deprived areas and broadband speed. The authors found that those who live in deprived areas tend to have lower broadband speed. Nevertheless Stocker and Whalley (2016) mentioned that whilst broadband speed is important for consumers' experiences it is not everything. The authors further explained that the relationship between broadband speed and consumers' experiences is likely to be an inverted U-shape. Therefore more understanding of the broadband dynamic is needed to develop appropriate broadband policy.

3. Methodology and data

3.1. Background on economic models

As suggested by Middleton (2013), broadband connections are not the same and there are huge differences between broadband speed connections in different areas. Even though broadband speed is not the only factor to determine the quality of broadband services there are a number of reports that support the idea that faster broadband speed increases the additional benefits. This study therefore analyses the impacts of broadband speed on economic outputs instead of broadband penetration as in previous studies. The econometric models of this paper follow the direct model from Thompson Jr. and Garbacz (2011) which applied a fixed effect with an endogenous adjustment to capture the direct impacts of broadband penetration. Compared with Rohman and Bohlin (2012), who were amongst the first to analyse broadband speed impacts, this paper adds further important variables such as gross fixed capital and divides the OECD countries based on their GDP per capita to investigate the impacts of broadband speed in countries with different income levels.

The models used in this paper are based on the Cobb-Douglas production function growth model. Other control variables are also added. Previous studies such as Koutroumpis (2009) and Thompson Jr. and Garbacz (2011) have similarly adapted this kind of model to broadband penetration. On the estimation approaches this study follows previous literature from Thompson Jr. and Garbacz (2011) and Rohman and Bohlin (2012) using 2SLS on panel data and the predicted value of broadband speed as a simultaneous (or triangular) approach to reduce endogeneity biases (A simultaneous approach has also been used by Röller and Waverman (2001), and Koutroumpis (2009) but these authors applied three stages instead of two). The panel data regression in this paper is presented in a simple fixed effect model as follows:

$$Y_{it} = X_{it}\beta + \alpha_i + u_{it} \qquad \text{for } t = 1, \ldots, T \text{ and } i = 1, \ldots, N. \qquad (1)$$

In this model, Y_{it} presents the dependent variable of individual (in this study, country) i at time t, X_{it} presents independent variables for individual i at time t, β presents the coefficient parameter of each independent variable, α_i presents the unobserved time-invariant individual effect, and u_{it} presents error terms. The endogeneity problem of panel data can arise if α_i or u_{it} is correlated with X_{it}. Whilst a fixed effect model can solve the correlation problem between α_i and X_{it}, the correlation or endogeneity problem between u_{it} and X_{it} needs more attention which is further discussed in Section 3.2.

3.2. Endogeneity problem and economic models

Similar to the studies on the effects of telecommunication services (computer, mobile telephony and broadband penetration) on economic outputs the estimated regressions of the model between broadband speed and economic outputs, such as GDP, are likely to suffer from endogeneity bias. The main concern of the endogeneity problem is a reverse causality. Whilst most studies aim to capture the effects of telecommunication services on economic outputs the development of telecommunication service could depend on economic development, especially in countries with high income which tend to invest more in telecommunication sectors due to the demand of their citizens. Another endogeneity bias could come from government intervention in the telecommunication sector because the intervention could also rely on the economic development of the country (Czernich, Falck, Kretschmer, & Woessman, 2011).

In the past decades many scholars have therefore applied different models to capture these endogeneity biases. Most studies adopted two-stage or three-stage least squares (2SLS or 3SLS) and used the predicted values of variables to solve or reduce these endogeneity biases. The details of the method varied between papers. Table 2 summarises different techniques used by previous studies on the effects of telecommunication services on economic outputs to cope with the endogeneity problem.

Whilst there are several methods to reduce endogeneity biases Thompson Jr. and Garbacz (2011) mentioned that truly exogenous variables are limited and that dealing with the endogeneity problem even with rigorous methods is usually successful on a small scale. The effects of broadband on economic outputs also differ by country.

Therefore this study provides the estimation of pooled OLS and IV approaches for the purpose of robustness. For the pooled OLS dummy variables for each country are included with robust standard errors to correct heteroskedasticity. For the IV approach the instrument variable is the percentage of fibre subscriptions of the total fixed broadband subscriptions. The reason for using the percentage of fibre subscriptions is that fibre technology generally contributes to higher broadband speed than other technologies and, at the same time, the ratio of fibre subscriptions to overall subscriptions is not likely to relate to economic outputs and other exogenous variables. Whilst correlation does not imply causation it is worth looking at the correlation between the

Table 2. Techniques used by previous studies to cope with the endogeneity problem

Author(s)	Main variable(s)	Methods to cope with the endogeneity problem/comments
Röller and Waverman (2001)	telecommunication infrastructure (proxy by main line penetration)	simultaneous approach by jointly estimated supply and demand with production equation (estimated with GMM[a])
Lehr et al. (2005)	broadband availability/ broadband penetration	matching control groups and treatment groups by estimating the average treatment effect
Crandall et al. (2007)	broadband infrastructure (by using broadband lines per population)	only use OLS[b] for simplicity, however, the authors stated that more complex methods failed to provide any significant difference from OLS
Koutroumpis (2009)	broadband infrastructure (proxy by broadband penetration)	a simultaneous approach by the jointly estimated supply and demand with a production equation (estimated with GMM and 3SLS)
Czernich et al. (2011)	broadband introduction/ broadband penetration	instrumental variable (IV) approach using the cable TV and voice telephone penetration rate as instruments
Thompson Jr. and Garbacz (2011)	fixed broadband lines per household/mobile broadband lines per household	estimating the predicted value for fixed broadband and mobile broadband using two-stage panel data regression (2SLS). The authors also suggested the stochastic frontier analysis to explain indirect broadband impacts
Rohman and Bohlin (2012)	broadband speed	two-stage panel data regression (2SLS) approach using broadband penetration, broadband price and telecom revenue to estimate broadband speed

[a] Generalised method of moments.
[b] Ordinary least squares.

Source: Compiled by the authors from various sources (as presented in Table 2).

chosen instrumental variable, the percentage of fibre subscriptions and other variables as in Table 3.

Table 3 suggests moderately strong and significant correlation between the percentage of the fibre subscriptions variable and the broadband speed variable. On the other hand the correlations between the percentage of the fibre subscriptions variable and other variables are insignificant or significant but weak in the case of the labour variable. Whilst the correlations of variables cannot confirm the validity of the choice of instrumental variable it can support

Table 3. Correlations between the percentage of fibre subscriptions and other variables

Variable(s)	ln $gdpc_{it}$	ln $capital_{it}$	$labour_{it}$	ln $speed_{it}$	$economic\_freedom_{it}$	$urban_{it}$
Correlation with $fibre\_percentage_{it}$	–0.0457 (0.2409)	0.0030 (0.9379)	0.1539*** (0.0001)	0.5157*** (0.0000)	–0.0571 (0.1370)	0.0395 (0.3034)

More descriptions of each variable are provided in Section 3.3.

The significance level of correlation coefficients are shown in parentheses.

*** Accounts for significant level at least at 1%.

the possibility that the percentage of fibre subscriptions can be a good instrumental variable for broadband speed.

For the simultaneous model with a predicted value of broadband speed 2SLS can be presented in two stages. The first stage is estimating the broadband speed variable based on the penetration rate of fixed broadband (the data for the penetration rate of mobile broadband are omitted due to the limitation of data availability) fibre ratio of fixed broadband penetration, GDP growth, population density and telecommunications revenue as a percentage of GDP. The second stage is estimating economic output which is GDP per capita based on fixed capital, labour, economic freedom, urban population ratio, a dummy variable for high income countries and the predicted value of broadband speed from the first stage. The purpose of the inclusion of a dummy variable for high income countries is for further analysis in Section 4. The first and second steps of the model are presented in (2) and (3). The descriptions of variables are provided in the next sub-section.

$$\ln speed_{it} = \alpha_0 + \alpha_1 fixed\_penetration_{it} + \alpha_2 fibre\_percentage_{it} + \\ + \alpha_3 GDPgrowth_{it} + \alpha_4 population\_density_{it} + \alpha_5 telecom\_revenue_{it} + u_{it}, \quad (2)$$

$$\ln gdpc_{it} = \beta_0 + \beta_1 \ln capital_{it} + \beta_2 labour_{it} + \beta_3 \ln speed_{it} + \\ + \beta_4 economic\_freedom_{it} + \beta_5 urban_{it} + \beta_6 income\_dummy_{it} + \varepsilon_{it}. \quad (3)$$

3.3. Variables and descriptive statistics

In this paper GDP per capita is chosen to represent the economic outputs of a country. Whilst GDP is by no means a perfect indicator to represent economic growth or country well-being it is still widely accepted by most private and public sectors, including researchers. It is so far one of the indicators generally used for describing the economic growth of a country. Similarly broadband speed, which is one of the characteristics of broadband services, cannot reflect all the impacts of broadband connection on a country's economy but it distinguishes one of the qualities of broadband services compared with only broadband penetration. In future broadband penetration is likely to be more stable and similar in many countries; hence broadband speed is the first step of differentiating between its services and impacts. As mentioned earlier in this paper research and reports have already suggested that faster speed broadband can stimulate more benefits in many ways. For other independent variables, fixed capital and labour force are included in the analysis based on the Cobb-Douglas production function growth model. Some socio-economic variables such as the economic freedom index, urban population ratio and a dummy variable for countries with a high income are also in the regression model as control variables for heterogeneity across the OECD countries. In the first step of the model, similarly to Rohman and Bohlin (2012), broadband speed can be closely considered as broadband development. The broadband speed vari-

Table 4. Variable descriptions

Variable	Description
$\ln gdpc_{it}$	the natural logarithm function of GDP per capita in thousands of US$ for country *i* at time *t*, volume estimates, fixed PPPs, OECD reference year, annual levels, seasonally adjusted
$\ln capital_{it}$	the natural logarithm function of gross fixed capital formation per capita in thousands of US$ for country *i* at time *t*, volume estimates, fixed PPPs, OECD reference year, annual levels, seasonally adjusted
$labour_{it}$	the ratio of total labour force to total population for country *i* at time *t*
$economic\_freedom_{it}$	the index of economic freedom, including ten freedom criteria from property rights to entrepreneurship (according to the heritage foundation website) for country *i* at time *t*
$urban_{it}$	the percentage of urban population per total population for country *i* at time *t*
$income\_dummy_{it}$	the dummy variable for high income countries for country *i* at time *t;* if GDP per capita > 30,000 US$ = 1, otherwise = 0
$\ln speed_{\mathrm{it}}$	the natural logarithm function of average broadband download speed in kilobits per second (Kbps) for country *i* at time *t*
$fixed\_penetration_{it}$	fixed broadband penetration per household for country *i* at time *t*
$fibre\_percentage_{it}$	the percentage of subscriptions of fibre technology of the total fixed broadband subscriptions for country *i* at time *t*
$GDPgrowth_{it}$	GDP growth rate for country *i* at time *t*
$population\_density_{it}$	population density (population per km^2 of land area) for country *i* at time *t*
$telecom\_revenue_{it}$	telecommunication revenue as a percentage of GDP from the previous year for country *i* at time *t*

able at the first stage therefore depends on fixed broadband penetration and population density for the demand side, whilst telecom revenue can be used as a proxy for telecom infrastructure for the supply side. Furthermore the model includes a fibre percentage of total fixed broadband and GDP growth. In general fibre technology currently has the ability to provide the highest speed; hence the ratio of fibre technology is likely to relate firmly to the speed of broadband services. Finally GDP growth is included to capture the reverse causality in the case of the citizens in the countries with high income being more likely to adopt new innovations such as ultra-fast speed broadband. Most variables are either in the form of a natural logarithm, ratio or index. The summary of variable specifications is presented in Table 4 and the summary of descriptive statistics in Table 5.

Table 5. Descriptive statistics summary

Variable	Observation	Mean	Std. Dev.	Min	Max
$gdpc_{it}$	660	30.0570	10.9238	11.0360	74.3432
$capital_{it}$	660	6.2268	2.4901	1.9623	18.1351
$labour_{it}$	660	0.5021	0.0589	0.3376	0.6905
$economic\_freedom_{it}$	660	71.8933	6.2194	58.8	83.1
$urban_{it}$	660	77.5449	11.3591	49.8998	97.5148
$income\_dummy_{it}$	660	0.5167	0.5001	0	1
$speed_{\mathbf{it}}$	654	10834.4	6655.6	1225.9	36588.4
$fixed\_penetration_{it}$	660	24.7941	8.3818	4.6440	41.9660
$fibre\_percentage_{it}$	660	8.9402	14.4335	0	64.9912
$GDPgrowth_{it}$	660	0.6280	3.4296	−14.0983	9.5579
$population\_density_{it}$	528	141.703	135.168	2.784	512.657
$telecom\_revenue_{it}$	652	2.8893	0.8305	1.1844	5.2049

Descriptive statistics for ln $gdpc_{it}$, ln $capital_{it}$ and ln $speed_{it}$ are summarised without the natural logarithm function as $gdpc_{it}$, $capital_{it}$ and $speed_{it}$.

3.4. Data sources

This paper uses broadband speed data from the Ookla website whilst other variables are based mainly on the OECD and World Bank statistics. The broadband speed data from Ookla are the download speed in kbps in the form of a combination of fixed and mobile broadband. The data are available on a daily basis. Monthly data are therefore obtained by taking the average of the daily data and the quarterly data are calculated by taking the average every three months. Other economic data sources in this study are based on the data from the OECD and World Bank statistics. For example GDP per capita and fixed capital data were obtained from the OECD whilst the labour force and urban population data were collected from World Bank statistics. The economic freedom index is available from http://www.heritage.org. Other data used in the first stage of the model are also based on the OECD and the World Bank (the fixed broadband penetration, percentage of fibre subscription and telecommunication revenue were from the OECD and the GDP growth and population density were from the World Bank).

4. Results

4.1. Empirical results

Table 6 illustrates five models on the impacts of broadband speed and other control variables on GDP per capita. All five models show significant results that higher speeds for broadband services encourage greater GDP per capita in the OECD countries. The Durbin–Wu–Hausman test in Table 6 suggests that the IV approach by using fibre percentage as the instrumental variable in model 2 and model 3 is more consistent than the use of the real values of broadband speed in both regression models. However for the purpose of consistency with previous literature such as Thompson Jr. and Garbacz (2011) and Rohman and Bohlin (2012), our preferred models which can be compared to previous studies are model 4 and model 5. The Hausman test suggests that the use of fixed effect in model 4 is more consistent than the use of random effect in model 5. As presented in Section 3.2 broadband speed variable is estimated according to equation (2). The regression result of the first-step to estimate predicted value of $lnspeed_{it}$ is in Table 8 in Appendix. According to the results from model 4 the coefficients of $lnspeed_{it}$ can be interpreted as a 10% increase in broadband speed positively affecting the GDP per capita by 0.8%. Other independent variables are also worth discussing. $lncapital_{it}$ and $labour_{it}$ have expected positive signs even though those for labour do not have significant results. This could be explained by the lack of education in the model; nevertheless education variables are only available for some countries. The level of economic freedom also has an expected positive sign; however it is insignificant in models 4 and 5. Lastly the significance of the dummy for income variables leads to the idea of further analysis as to how broadband speed can affect the GDP per capita in countries with different income levels. The data are now divided into two groups based on the GDP per capita with 16 countries in the lower group and 17 countries in the higher group. The estimation approach, 2SLS with predicted value for broadband speed (similar to Model 4 and Model 5 from Table 6), is applied to investigate this issue.

Table 6. Regression results: impacts of broadband speed and other control variables on GDP per capita

Variable(s)	Model 1	Model 2	Model 3	Model 4	Model 5
Dependent variable: ln $gdpc_{it}$ **Independent variables**					
ln $capital_{it}$	0.2173***	0.2466***	0.2429***	0.1894***	0.1970***
$labour_{it}$	0.4635***	–0.1223	0.2090	0.5533	0.6809
ln $speed_{it}^{a}$	0.0147***	0.0479***	0.0352***	0.0807***	0.0699***
$ec\_freedom_{it}$	0.0016**	0.0030***	0.0029***	0.0017	0.0018
$urban_{it}$	0.0091***	–0.0049	0.0038*	–0.0065*	0.0025
$income_{it}$	0.0251***	0.0187*	0.0360***	0.0212***	0.0344***
constant	1.7092***	2.6794***	1.9661***	2.3649***	1.6742***
R-squared	0.9973	0.5185	0.7592	0.6940	0.7419
Prob>F/Prob>χ^2	0.0000***	0.0000***	0.0000***	0.0000***	0.0000***
Durbin-Wu-Hausman test (χ^2)	–	13.93**	12.79**	–	–
Hausman test (χ^2)	–	330.34***		109.50***	
obs	654	654	654	520	520

[a] ln $speed_{it}$: the real values of ln $speed_{it}$ are only used in model 1, ln $speed_{it}$ in model 2, and model 3 is instrumented by fibre_percentage, and ln $speed_{it}$ in models 4 and 5 is the predicted value from the penetration rate of fixed broadband, fibre_percentage, GDP growth, population density and telecom revenue.
Model 1: pooled OLS with country dummies, model 2: IV-FE (instrumented by $fibre\_percentage_{it}$), model 3: IV-RE (instrumented by $fibre\_percentage_{it}$), model 4: 2SLS-FE (with predicted value for ln $speed_{it}$), model 5: 2SLS-RE (with predicted value for ln $speed_{it}$).
The significant level is reported using ***, ** and *. *** significant at 1%, ** significant at 5% and * significant at 10%.

Table 7 further analyses the impacts of broadband speed on GDP per capita by comparing high income countries and low income countries. The results from the Hausman test show that model 6 is preferred to model 7 for the lower income countries, and model 8 is preferred to model 9 for the higher income countries. In comparison, the coefficient of model 6, 0.0975, is higher than the one in model 8, 0.0591 (both are significant at least at the 1% level). These results imply that broadband speed has greater impact in countries with lower income than countries with higher income. These results are also consistent with Thompson Jr. and Garbacz (2011). The authors found that mobile broadband has greater positive effects in poorer countries than in higher income countries. Other interesting variables from Table 7 are $labour_{it}$ and $economic\_freedom_{it}$. These two variables are significant and have higher positive impacts on GDP

Table 7. Regression results: impacts of broadband speed on GDP per capita, comparing lower income countries and higher income countries

Variable(s)	Model 6	Model 7	Model 8	Model 9
Dependent variable: ln $gdpc_{it}$ **Independent variables**				
ln $capital_{it}$	0.2416***	0.2498***	0.1590***	0.1651***
$labour_{it}$	0.7272**	0.5526**	–0.3076	–0.3277
ln $speed_{it}^{a}$	0.0975***	0.0906***	0.0591***	0.0507***
$ec\_freedom_{it}$	0.0042**	0.0037**	0.0011	0.0009
$urban_{it}$	–0.0107**	–0.0026	–0.0122**	–0.0065***
constant	1.9422***	1.5338***	3.8362***	3.4621***
R-squared	0.8167	0.6209	0.6106	0.3659
Prob>F/Chi2	0.0000***	0.0000***	0.0000***	0.0000***
Hausman test	Chi2=44.94***		Chi2=13.16**	
obs	248	248	272	272

[a] ln $speed_{it}$: ln $speed_{it}$ in models 6,7,8 and 9 is the predicted value from the penetration rate of fixed broadband, fibre_percentage, GDP growth, population density and telecom revenue.
Models 6 and 7 are replicated from models 4 and 5 but only for countries with lower income.
Models 8 and 9 are also replicated from models 4 and 5 but only for countries with higher income.
The OECD countries are split into two groups, one with the higher average GDP per capita and the other with the lower income countries.
The significant level is reported using ***, ** and *. *** significant at 1%, ** significant at 5% and * significant at 10%.

per capita also in lower income countries. These results could imply that the level of economic freedom and labour still have important roles in relation to economic growth in lower income countries. On the other hand the effects of the level of economic freedom and labour in higher income countries are less significant compared with lower income countries.

4.2. Limitations

There are some limitations on the data used in this study. First, the data from Greece is omitted from the analysis due to missing data on GDP and cost of capital. Furthermore even though the broadband speed variable includes both fixed and mobile broadband the mobile broadband penetration is omitted from the first stage of the analysis because of limited availability. Whilst all five models in Table 6 suggest significant positive impacts of broadband speed on GDP per capita the values of the coefficients vary from 0.01 to 0.08 depending on the models. Even though our preferred model (model 4) can be interpreted as an increase in broadband speed of 10% leading to an increase in GDP per capita of 0.8% it is important to realise that these exact numbers of the coefficients should be interpreted with caution. This study does not aim to quantify the exact effects of broadband speed on GDP. Instead it points out the importance of high speed broadband since the causality of high speed broadband and economic outputs in all the models show that the results in all models are consistent and that broadband speed does matter. With regard as to whether the relationship between broadband speed and economic output is linear or non-linear the results from Table 7 imply that different countries have different impacts of broadband speed on the economic outputs (higher positive impacts on lower income countries). It is therefore possible that the relationship of broadband speed on economic output is positive but at a decreasing rate.[5] Nevertheless models in Table 6 and Table 7 are set in a linear relationship for the simplicity of analysis. Lastly, the analysis of this study is set in the static framework because the dataset does not fit with the dynamic framework. In addition, adding the lagged variable in the dynamic analysis requires many more untestable assumptions compared to the static panel data analysis (Brüderl, 2005). Thus the dynamic framework with an improved dataset can be extended for future studies.

Conclusions

As presented in Section 4 all the models provide significant positive coefficients and the results of this study are robust. The results are also consistent with previous studies related to broadband speed (Katz, Vaterlaus, Zenhäusern, & Suter, 2010; Rohman & Bohlin, 2012; Forzati & Mattsson, 2012) that faster broadband speed encourages greater benefits for a country; in this case it stimulates higher GDP per capita. These results also imply an importance of national broadband plans that aim for higher broadband speed. Whilst achieving broadband penetration targets are still important improving the quality of the services, such as greater broadband speed, also leads to higher economic outputs of the countries. As mentioned in Section 1 a higher broadband speed benefits economic outputs through many aspects including faster and more efficient work processes in other sectors. For the latter part in respect of Table 6 the results further emphasise the importance of higher broadband speed, especially in countries with lower income. Even though this paper focuses on the OECD countries the findings on the impacts in lower income countries can also be applied to other developing countries: faster broadband services have greater impacts to stimulate their economic growth. The reason behind this is that in

[5] Table 9 in the Appendix supports this argument by showing simple fixed and random effect models including the square of variable $lnspeed_{it}$.

the lower income countries the use of new technology and the replacement rate of older technology is growing at a faster pace (Thompson Jr. & Garbacz, 2011).

Nevertheless it is important to realise that it is not only the speed that matters to users: economic growth and society, the quality of the services and the way consumers use the network also matter. Whilst this study cannot capture the impact of every aspect of broadband on economic growth, nor quantify the exact numbers of impacts of broadband speed on economic outputs, it focuses on and supports the hypothesis that greater broadband speed benefits society by stimulating economic outputs such as GDP per capita. The significance of at least a 10% level in all models also confirms the robustness of the results. This study not only enriches the empirical research of the broadband speed study, which is limited, but it also recommends that policy-makers should adopt the development of higher broadband speed into their broadband policy or national broadband plan. For future research this study only covers the static model. The next interesting step for future research would be to analyse in a dynamic framework. The analysis of broadband speed at micro-level of a particular country or region is also important to consider, along with a study at macro-level. Whilst the macro-level study can provide the general guideline for policy-makers, the micro-level study provides more detail on a specific area. Finally, other characteristics such as quality of broadband services or type of broadband technology are also interesting for future research.

Appendix

Table 8. First stage of regression for the predicted value of ln $speed_{it}$

Variable(s)	Coefficient(s)
Dependent variable: ln $speed_{it}$ **Independent variable(s)**	
$fixed\_penetration_{it}$	0.0465***
$fibre\_percentage_{it}$	0.0175***
GDP_growth_{it}	0.0255***
$population\_density_{it}$	0.00004
$telecom\_revenue_{it}$	0.0820***
constant	7.4760***
Prob>F	0.0000***
R-squared	0.6558
obs	530

The significant level is reported using ***, ** and *. *** significant at 1%, ** significant at 5% and * significant at 10%.

Table 9. Regression results: impacts of broadband speed and other control variables including the square of ln $speed_{it}$ (ln $speedsq_{it}$) on GDP per capita

Variable(s)	Fixed effect coefficient(s)	Random effect coefficient(s)
Dependent variable: ln $gdpc_{it}$ **Independent variable(s)**		
ln $capital_{it}$	0.2219***	0.2252***
$labour_{it}$	0.3207**	0.4606***
ln $speed_{it}$	0.1290***	0.1224***
$ec\_freedom_{it}$	0.0013*	0.0013*
$urban_{it}$	0.0094***	0.0083***
$income_{it}$	0.0256***	0.0361***
ln $speedsq_{it}$	–0.0063***	–0.0059***
constant	1.3071***	1.3381***
R-squared	0.6285	0.6378
Prob>F/Chi2	0.0000***	0.0000***
Hausman test	Chi2 = 89.49***	
obs	654	654

The significant level is reported using ***, ** and *. *** significant at 1%, ** significant at 5% and * significant at 10%.

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