How Important is Mobile Broadband Latency for Total Factor Productivity Growth?

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Abstract: This paper investigates the relationship between the log change in mobile broadband latency and total factor productivity (TFP) growth based on data for 130 countries. It finds that there is a strong negative correlation between TFP growth and one year lag of latency growth in OECD countries. The interpretation of the findings is that a 10 percentage points decrease in the growth of latency in period t-1 is associated with an increase of 0.3 percentage points in TFP growth. The findings are in accordance with the framework of General Purpose Technologies that suggests that the impact of new technologies often appear with a lag. Moreover, no relationship is found for the total sample or for non-OECD countries. One possible explanation could be that OECD countries have reached a higher maturity in digitalisation and automation in production processes and thus are able to take advantage of the benefits of lower latency.

Keywords: ICT, Productivity, Latency, Mobile broadband networks, Economic development

Introduction

During the last decade there has been a substantial decline in productivity growth in many OECD countries. Figure 1 shows labour productivity growth for the largest economies in the world 1995–2021. The average labour productivity growth in the OECD countries decreased from 1.4 percent in 1995–2010 to 0.9 percent in 2010–2021. The average labour productivity growth in the world increased from 2.1 percent to 2.2 percent for the same periods, respectively. Similar results have been found for total factor productivity (TFP), which is a measure that in addition to labour also includes the contributions of physical, human and other intangible capital (De Vries, 2023). Thus, productivity growth has been considerably lower in OECD countries, compared to the rest of the world.

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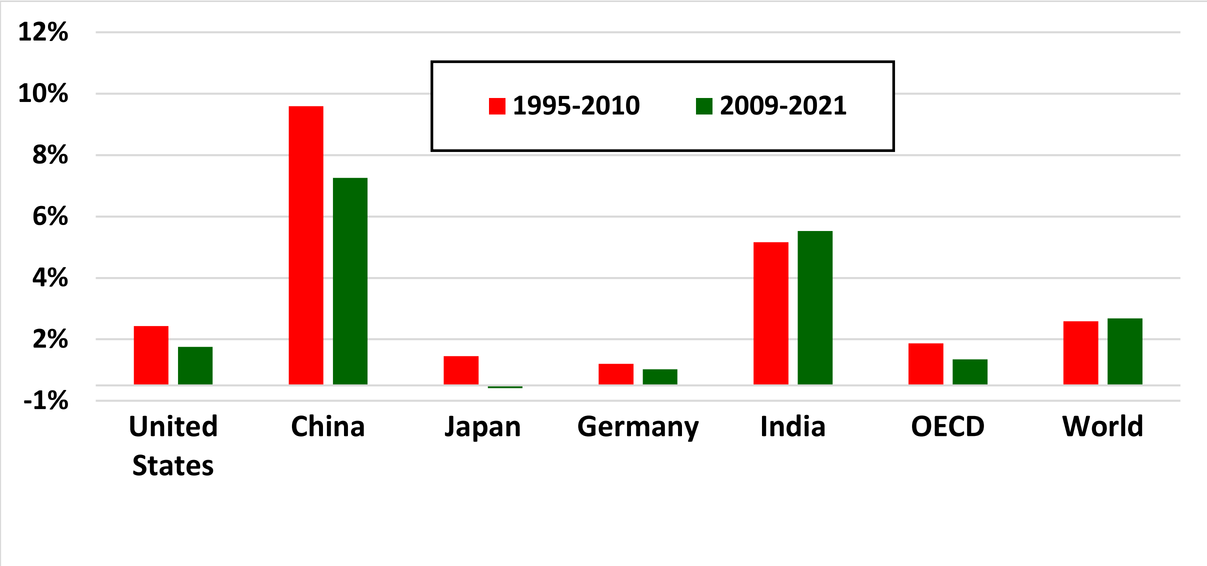

Figure 1. Annual labour productivity growth measured as GDP per person employed (constant 2017 PPP $) in the five largest economies of the world 1995–2021 (Source: World Bank, 2023a)

Over the last decade there has been large investment in new digital infrastructure e.g. 5G (5th generation mobile network) that was launched in several OECD countries in 2019. Moreover, there was also substantial investment in fixed broadband during the pandemic (ITU, 2021). The investment has improved the capabilities in the networks tremendously in terms of speed, latency, spectrum efficiency and reliability. This has implied improved high-speed connectivity that has made it possible to connect billions of devices to the cellular networks.

Despite the improved network capabilities, the productivity growth in many OECD countries has been poor. Some economists have even argued that the Solow paradox (i.e., productivity slowdown, despite progress in information and communication technology) is back at the same time as a second wave of digitalisation sweeps the world (Acemoglu *et al.*, 2014). This paper sets out to investigate the link between investment in network capabilities and productivity growth. The paper will focus on the impact of lower latency in the cellular networks and its association with productivity growth.

Latency is the time it takes for a small data packet to travel across a network from a sender to a receiver. Several studies have investigated the impact from broadband speed on economic development (see Rohman & Bohlin, 2012; Kongaut & Bohlin, 2014; Edquist, 2022). However, there is, to my knowledge, no study that has investigated how latency affects productivity development. Therefore, this paper will contribute to the literature by investigating the effect from ICT (information and communication technology) on productivity development. The methodology will start from the theory of production functions, in order to specify a model investigating the correlation between latency and TFP. The empirical analysis will be based on econometric methodology utilizing panel data for 130 countries.

The findings show a strong correlation between TFP growth and one year lag of latency growth, once controlling for labour and capital services, in OECD countries. Thus, a 10 percentage points decrease in the growth of latency in period t-1 is associated with an increase of 0.3 percentage points in TFP growth. Moreover, no relationship is found for non-OECD countries. One possible explanation could be that OECD countries have reached a higher maturity in digitalisation and automation in production processes and thus are able to take advantage of the benefits of lower latency.

Previous Literature

The relationship between ICT and economic development

There is a broad literature showing that ICT has had substantial impact on economic development and productivity (Bertschek *et al.*, 2015; Vu *et al.*, 2020). The 1980s was the decade of the personal computer in every home without any discernable effect on aggregated productivity (Solow, 1987). Thus, it was first in the second half of the 1990s that there was substantial evidence of investment in ICT having considerable economic impact. Oliner & Sichel (2000) estimated that information technology accounted for about two-thirds of the step-up in US labour productivity growth between the first and the second halves of the 1990s.

Although there were sceptics about the impact from ICT (Gordon, 2000), a number of studies clearly found evidence of a substantial impact on productivity and economic growth from ICT. Stiroh (2002b) found that ICT-producing and intensive ICT-using industries accounted for all of the productivity revival in the US. Moreover, ICT remained an important source of economic growth in the US also after the 1990s (Jorgenson *et al.*, 2008). Van Ark et al. (2008) noted that many European countries initially were lagging behind because of slower TFP growth in market services, such as trade, finance and business services. However, the overall impact of ICT capital in 59 different countries pointed towards a positive effect on GDP growth in 1995–2010 (Niebel, 2018).

In the mid-1990s there was additional evidence of the economic impact of ICT at more disaggregated levels. Basu & Fernald (2007) found that, with long time lags, ICT capital growth was positively associated with the industry TFP acceleration. Additional evidence based on industry data showed a positive return of ICT capital on output growth (O'Mahony & Vecchi, 2005). Moreover, there was evidence that European industries, that were relatively ICT intensive before 1995, outperformed the other industries post-1995 in terms of both labour productivity and TFP growth (Dahl *et al.*, 2010). There were also studies that could not find robust correlations between ICT and economic development based on industry data

(Stiroh 2005; Basu *et al.*, 2003). However, the overall conclusion based on the literature points in the direction of positive correlations between ICT and economic development.

Research, analyzing the firm level, found a robust relationship between ICT and economic development. Brynjolfsson & Hitt (2003) showed that computer capital was correlated with TFP growth for US firms when the average growth rates over longer time periods were used. The results were not robust to using first differences, but the estimated coefficients increased in size when the length of the growth period increased. Additional studies found evidence of economic impact from ICT at the firm level (van Leeuwen & van der Wiel, 2003; Van Reenen *et al.*, 2010; Zhang *et al.*, 2022). Moreover, based on two European datasets, it was also shown that US multinationals appeared to obtain higher productivity than non-US multinationals from their ICT capital investments (Bloom *et al.*, 2012). Thus, ICT may lead to changes in firms' organisational structure that differs across firms.

Investigations of the "C" in ICT

While there has been a plethora of papers investigating the economic impact of all types of ICTs, there is much less research investigating the impacts of specific varieties of ICT equipment. Goodridge et al. (2019) divided ICT capital into computer software, hardware, and communication capital. Their findings suggested that price deflators are important for estimating the contribution of each capital type.

In a seminal paper, Röller & Waverman (2001) found a significant relationship between telecommunications infrastructure and aggregate output based on 21 OECD countries in 1971–1990. Their findings suggested that one-third of economic growth could be attributed to telecommunications after controlling for simultaneity and country-specific fixed effects. Moreover, Gruber & Koutroumpis (2011), based on data for 192 countries, found that investment in telecommunications infrastructure contributed 0.2 percentage points to economic growth in high income countries in 1990–2007.

There are also a number of papers investigating the impact of fixed broadband. Czernich et al. (2011) found that a 10 percentage points increase in fixed broadband penetration raised annual per capita growth by 0.9–1.5 percentage points in 21 OECD countries in 1996–2007. Gruber et al. (2014) also found evidence that fixed broadband had a positive effect on GDP for 27 EU-countries in 2005–2011. On the contrary, Thomson & Garbacz (2011) found no strong significant impact from fixed broadband adoption on GDP per household based on 43 different countries in 2005–2009. However, the results based on mobile broadband suggested a significant impact on GDP per household. Moreover, Edquist et al. (2018) found that there was a statistically significant effect from mobile broadband on GDP in 2002–2014. The results

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were significant both when mobile broadband was first introduced and gradually as it diffused in different economies.

An additional stream of papers has investigated the economic impact from different capabilities of fixed and mobile broadband networks. These studies are primarily focused on the effect of download speed in the networks. Briglauer & Gugler (2019) found a small but significant effect of fixed fibre-based adoption on GDP compared to basic fixed broadband. Rohman & Bohlin (2012) showed that the doubling of fixed broadband speed contributed 0.3 percentage points to economic growth compared to growth rate in the base year in 34 OECD countries. Additional studies have found supporting evidence that fixed broadband speed contributed to GDP, but that the impact was greater in countries with lower incomes (Kongaut & Bohlin, 2014). Moreover, Edquist (2022) investigated the impact of download speed in the mobile broadband networks in 116 countries in 2014–2019. The results showed that a one-year lag of median download speed was significantly associated with labour productivity, but there was no evidence of a contemporaneous association.

General purpose technologies and the lagged effect

According to Bresnahan & Trajtenberg (1995), whole eras of technical progress are driven by a few General Purpose Technologies (GPTs) with the following characteristics: (1) pervasiveness, which implies that the technology diffuses extensively throughout the economy; (2) technical improvements, meaning that the technology continuously improves performance and lowers cost; (3) innovational complementarities, implying that the technology leads to improvements in R&D and innovational efforts.

The effects from GPTs on productivity are often delayed, since many GPTs require organizational restructuring to reach their full potential (Helpman, 1998). At first, the new technology may only perform the same function as the old technology, which was the case when electric motors replaced steam engines in the early 20th century (Devine, 1983). However, as more electric motors were installed in factories, it was possible to let each machine be run by an individual electric motor and thus reorganise the whole production layout of the factory in a more productive manner. According to Greenwood (1999), it was no longer necessary to shut down the entire power system for maintenance. Thus, the quantity and quality of output increased as each machine could be controlled individually and located to optimise flexibility in the production process. This process implied that existing productive capital was creatively destroyed, which further delayed the positive productivity effects at the more aggregate level.

According to the GPT literature, another reason for the delayed productivity effects from new technology is innovational complementarities. An invention by itself would have little

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economic effect if there was no scope for the users of the new technology to improve their own technologies (Edquist & Henrekson, 2006). For example, before electricity could be used in manufacturing, several types of electric machines had to be invented. Hence, it is rather the applications of a wireless network that result in productivity gains than the network by itself.

ICT is believed to fulfill the requirements of being a GPT (Vu *et al.*, 2020). There are a number of different studies that have pointed out that the effects on productivity from new technology often appear with a lag (David, 1990; Brynjolfsson & Hitt, 2003; Edquist & Henrekson, 2017). These empirical findings support the view of the GPT framework that it takes time from the moment of the original invention until a substantial increase in the rate of productivity growth can be observed.

Latency and its implications for productivity

Latency is the time it takes for a small data packet to travel across the network from a sender to a receiver and for the response to come back (Sundaresan *et al.*, 2020). This way of measuring latency is known as Round Trip Time (RTT). RTT is the latency perceived by the end-user (NGNM, 2015). There is also one way-latency, which is the total time it takes for a packet of data to travel from the sender to the receiver. According to Sundaresan et al. (2020), it may be complicated to measure one-way latency as it implies that the sender and receiver have synchronised clocks, which sometimes is a challenge to set up and maintain when the end points are across multiple domains.

Data on the Internet may travel with the speed of light, but the effects of distance and delays caused by the Internet infrastructure equipment imply that latency cannot be completely eliminated. Moreover, data traversing the Internet often has to cross multiple networks. The more networks the data packet needs to pass through, the larger is the probability of delay.

As the world has become more digital, the impact from latency on productivity is believed to have increased substantially. One reason is that businesses have become more reliant on cloud applications (Dar, 2018). In recent years it has become common that employees use video conferencing for sales purposes and information sharing. Moreover, cloud-based management tools are used to access information, share files and perform business processes. It is evident that high latency will slow down these processes, which most certainly also effects the productivity among employees.

In the last year the impact from Internet of Things (IoT) have become increasingly important for productivity (Edquist *et al.*, 2021). The interconnected devices that are used for personal and business tasks are dependent on the fast transfer of information. Thus, latency and reliability play a vital role in the smooth operations of IoT devices (Siddiqi *et al.*, 2019).

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Methodology

To investigate the association between latency and total factor productivity (TFP), the methodology in this paper is based on econometric methods. The econometric model in this paper follows the neoclassical production function (Solow, 1956). Assuming an augmented Cobb-Douglas production function (Cobb & Douglas, 1928), we have the following equation:

$$V_{i,t} = TFP_{i,t} K_{i,t}^{S_K} L_{i,t}^{S_L} \quad (1)$$

where $V_{i,t}$ is real value added, $K_{i,t}$ is capital, $L_{i,t}$ is labour input, S_K is the output elasticity of capital, S_L is the output elasticity of labour and $TFP_{i,t}$ is Hicks-neutral TFP, all for country *i* at time *t*.

Taking natural logarithms of and first differencing equation (1) gives:

$$\Delta \ln V_{i,t} = s_K \Delta \ln K_{i,t} + s_L \Delta \ln L_{i,t} + \Delta \ln TFP_{i,t} \quad (2)$$

Based on the growth accounting framework it is assumed that markets are competitive and there are constant returns to scale, which implies that the elasticities S_K and S_L are equal to each factor's income share (Solow, 1957). Thus, by transforming equation (2), TFP can be estimated as follows:

$$\Delta \ln TFP_{i,t} = \Delta \ln V_{i,t} - s_K \Delta \ln K_{i,t} - s_L \Delta \ln L_{i,t} \quad (3)$$

Equation (3) shows that ΔTFP is measured as a residual, which implies that there might be measurement errors in capital and labour inputs. Moreover, there might also be unmeasured intangible capital (Corrado *et al.*, 2009; Marrano *et al.*, 2009). However, TFP could also be caused by organizing production processes in a smarter (more productive) way (Stiroh, 2002a).

Lower latency improves the quality of a network and primarily affects cloud and IoT applications, which in the longer run leads to reorganization and rationalization. Thus, it is likely that latency would be affecting TFP growth. These productivity enhancing applications can first be fully acknowledged once the latency has been reduced to a certain level. Moreover, the GPT literature suggests that the productivity effects would take time due to reorganizations of production. It would therefore be of interest to estimate an equation that tests whether latency is correlated with TFP growth. The econometric specification is based on first differences in order to control for country fixed effects.

$$\Delta \ln TFP_{i,t} = \beta_1 + \beta_2 \Delta \ln Latency_{i,t} + \beta_3 \Delta \ln K_{i,t} + \beta_4 \Delta \ln LS_{i,t} + \beta_5 \Delta \ln X_{i,t} + \delta_t + v_{i,t} \quad (4)$$

where $\Delta lnTFP_{i,t}$ is the change in log TFP in country *i*, $\Delta lnLatency_{i,t}$ is the change in log latency, $\Delta lnK_{i,t}$ is the change in log capital services, $\Delta lnLS_{i,t}$ is the change in log labour services, $\Delta lnX_{i,t}$

is the change in any additional control variables, δ_t are year dummies which capture common economic shocks, and $v_{i,t}$ is the differenced residual.

As shown above, TFP is measured as a residual in a growth accounting framework. This implies that TFP is only measured in terms of first differences and not in level estimates. Moreover, the concept of the level of capital services is also unclear (Inklaar & Timmer, 2008). Therefore, the specification will be based on first differences. By using first differences it is still possible to control for country fixed effects. However, it will not be possible to conduct panel data analysis based on levels.

Data

The purpose of this paper is primarily to investigate the association between TFP and latency in the cellular network. The dependent variable TFP growth is based on the Total Economy Database (Conference Board, 2022). It is measured as a residual and accounts for the changes in output not caused directly by change in capital and labour services. Thus, it represents the effect of technological change, efficiency improvements, innovation and inability to measure the contribution of all other inputs (De Vries & Erumban, 2022).

The main independent variable of interest is latency. Latency data is based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021 (Ookla, 2022). The database presents data from millions of tests and readings collected via Speedtest, which is an app service used to test the speed and latency of a particular mobile device. Latency is measured as round-trip time (RTT) in milliseconds. One potential bias with collecting the latency data is that people might be more eager to run the speed test when they are close to a base station. Moreover, it is also likely that many users run the speed test when the network is not working appropriately. To minimise these measurement errors, the median latency is used instead of the average latency. Moreover, as long as these biases are similar among countries, the measurement error will be similar in all countries.

According to the production function theory, the growth of capital and labour services should be included as additional independent variables. The data of the growth of capital and labour services and TFP are based on the Total Economy Database (Conference Board, 2022). Capital services growth refers to the change in the flow of productive services provided by capital assets, such as buildings, transport equipment and machines. The underlying capital stock is based on six different asset types that are calculated from national accounts' investment data using the perpetual inventory method. The aggregation of the growth in capital over the different types is based on a user cost approach (De Vries & Erumban, 2022). Labour services have been constructed by aggregating the change in labour quantity and quality. Labour quantity is based on total hours worked or total persons engaged, while labour quality is based

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on a measure in the changes of the composition of the workforce, which is based on data on employment and wages by educational attainment.

In the robustness section, we introduce mobile download speed as an additional independent variable. Download speed data is based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021 (Ookla, 2022). Download speed is measured in kilobits per second (kbps). There are a number of research articles that have found associations between economic development and speed in fixed and cellular networks (i.e., Briglauer & Gugler, 2019; Rohman & Bohlin, 2012; Kongaut & Bohlin, 2014; Edquist, 2022). In addition to speed, the change in the size of manufacturing in each country (measured as the share of GDP in percent) is also included as a control variable. The manufacturing share is based on the World Bank (2023a). The change in the size of manufacturing may have an impact on TFP as Internet of Things and machine learning are believed to have a larger impact in manufacturing.

Table 1. Countries included in the regressions divided into OECD and non-OECD countries

OECD countries (38)	Australia, Austria, Belgium, Canada, Chile, Colombia, Costa Rica, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovakia, Slovenia, South Korea, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States
Non-OECD countries (92)	Albania, Algeria*, Angola*, Argentina, Armenia, Azerbaijan, Bahrain, Bangladesh*, Belarus, Bolivia*, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Burkina Faso*, Cambodia*, Cameroon*, Chad*, China, Congo*, Croatia, Cyprus, Côte d'Ivoire*, DR Congo*, Dominican Republic, Ecuador, Egypt*, Ethiopia*, Gabon, Georgia, Ghana*, Guatemala, Hong Kong, India*, Indonesia*, Iran*, Iraq, Jamaica, Jordan, Kazakhstan, Kenya*, Kuwait, Kyrgyzstan*, Lebanon*, Libya, Madagascar*, Malawi*, Malaysia, Mali*, Malta, Mauritius, Moldova, Morocco*, Mozambique*, Myanmar*, Namibia, Niger*, Nigeria*, North Macedonia, Oman, Pakistan*, Paraguay, Peru, Philippines*, Qatar, Romania, Russia, Rwanda*, Saudi Arabia, Senegal*, Serbia, Singapore, South Africa, Sri Lanka*, Sudan*, Syria*, Taiwan, Tanzania*, Thailand, Trinidad and Tobago, Tunisia*, Turkmenistan, Uganda*, Ukraine*, United Arab Emirates, Uruguay, Uzbekistan*, Venezuela, Vietnam*, Yemen*, Zambia*, Zimbabwe*

Note: *indicates that the country is defined as a low-income country i.e. has GNI per capita below $4256.

In total, data for 130 countries are used in the regression analysis for the period 2014–2021. The analysis is based on a balanced panel for all variables included in the respective regressions. Thus, all countries with missing data for a specific variable that is included in the specific regression analysis have been dropped. Table 1 shows a list of the countries that have been included in the regressions, divided into OECD and non-OECD countries. Moreover, Table 2 shows some descriptive statistics.

Table 2. Descriptive statistics (2014–2021)

Variables	Mean	St. Dev.	Min	Max	No. obs
All countries					
Log change in total factor productivity (ΔlnTFP)	−0.008	0.05	−0.85	0.50	910
Log change in median latency (ΔlnLatency)	−0.19	0.26	−1.76	1.05	910
Log change in labour services (ΔlnLS)	0.006	0.01	−0.05	0.17	910
Log change in capital services (ΔlnK)	0.04	0.03	−0.08	0.19	910
Log change in download speed (ΔlnSpeed)	0.30	0.34	−0.83	2.93	910
Change in the share of manufacturing (in % of GDP) (ΔMfg)	0.05	1.03	−7.76	15.11	798
OECD countries					
Log change in total factor productivity (ΔlnTFP)	0.0006	0.02	−0.14	0.07	266
Log change in median latency (ΔlnLatency)	−0.13	0.13	−0.78	0.09	266
Log change in labour services (ΔlnLS)	0.005	0.007	−0.04	0.04	266
Log change in capital services (ΔlnK)	0.03	0.02	−0.01	0.19	266
Log change in download speed (ΔlnSpeed)	0.25	0.20	−0.37	1.07	266
Change in the share of manufacturing (in % of GDP) (ΔMfg)	0.04	1.11	−1.66	15.11	252
Non-OECD countries					
Log change in total factor productivity (ΔlnTFP)	−0.01	0.06	−0.85	0.50	644
Log change in median latency (ΔlnLatency)	−0.22	0.29	−1.76	1.05	644
Log change in labour services (ΔlnLS)	0.006	0.01	−0.05	0.17	644
Log change in capital services (ΔlnK)	0.04	0.04	−0.08	0.18	644
Log change in download speed (ΔlnSpeed)	0.32	0.38	−0.83	2.93	644
Change in the share of manufacturing (in % of GDP) (ΔMfg)	0.06	0.99	−7.76	7.84	546

Note: Latency and download speed data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021.

Results

Main results

Table 3 presents the aggregate result based on the total sample of 130 countries. It shows that there is no significant relationship between TFP growth and the change in log of mobile broadband latency. Moreover, when three years differences are included, there is still no evidence of any significant relationship.

Table 4 includes the change in log of latency that has been lagged by one year. However, there is still no significant correlation between the lagged latency variable and TFP growth. Moreover, when we include both the change in the log of latency and its lag, there is no significant correlation with TFP growth. Thus, there is little evidence of any association between TFP growth and the change in the log of latency for our total sample of 130 countries.

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Table 3. Regressions of the relationship between TFP growth and the change in the log of latency

	Dependent variable: TFP growth (ΔlnTFP)	
	First differences	Three years differences
ΔLog of latency (ΔlnLatency)	−0.002 (0.008)	−0.02 (0.020)
ΔLog of labour services (ΔlnLS)	−0.33*** (0.099)	−0.23 (0.308)
ΔLog of capital services (ΔlnK)	0.01 (0.141)	0.04 (0.176)
Constant	−0.007 (0.009)	−0.03 (0.032)
Year dummies	Yes	Yes
R^2	0.06	0.04
Number of observations	910	650

Note: The estimates are based on pooled Ordinary Least Squares (OLS). Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Latency data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021.

Table 4. Regressions of the relationship between TFP growth and the change in the log and lagged log of latency

	Dependent variable: TFP growth (ΔlnTFP)		
	First differences	Lagged differences	First + lagged differences
ΔLog of latency (ΔlnLatency)	−0.002 (0.008)		−0.009 (0.011)
ΔLog of latency (ΔlnLatency) (t−1)		−0.005 (0.006)	−0.005 (0.006)
ΔLog of labour services (ΔlnLS)	−0.33*** (0.099)	−0.28** (0.119)	−0.29** (0.118)
ΔLog of capital services (ΔlnK)	0.01 (0.141)	−0.003 (0.159)	−0.005 (0.160)
Constant	−0.007 (0.009)	−0.009 (0.010)	−0.01 (0.010)
Year dummies	Yes	Yes	Yes
R^2	0.06	0.06	0.07
Number of observations	910	780	780

Note: The estimates are based on pooled Ordinary Least Squares (OLS). Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Latency data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021.

To further investigate the impact from latency, the sample is divided into OECD and non-OECD countries. Table 5 shows that there is still no significant relationship between the change in log of mobile broadband latency and TFP growth in OECD and non-OECD countries, respectively. The same holds for three years differences.

Table 5. Regressions of the relationship between TFP growth and the change in the log of latency for OECD and non-OECD countries

	Dependent variable: TFP growth (ΔlnTFP)			
	First differences		Three years differences	
	OECD	Non-OECD	OECD	Non-OECD
ΔLog of latency (ΔlnLatency)	0.004 (0.012)	−0.007 (0.009)	−0.012 (0.021)	−0.03 (0.023)
ΔLog of labour services (ΔlnLS)	−0.14 (0.230)	−0.32*** (0.119)	−0.03 (0.373)	−0.10 (0.395)
ΔLog of capital services (ΔlnK)	−0.29 (0.233)	0.08 (0.158)	−0.25 (0.239)	0.11 (0.200)
Constant	0.01* (0.008)	−0.018 (0.012)	0.03 (0.021)	−0.07 (0.049)
Year dummies	Yes	Yes	Yes	Yes
R^2	0.31	0.05	0.20	0.05
Number of observations	266	644	190	460

Note: The estimates are based on pooled Ordinary Least Squares (OLS). Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Latency data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021.

Table 6. Regressions of the relationship between TFP growth and the change in the log and lagged log of latency

	Dependent variable: TFP growth (ΔlnTFP)					
	First differences		Lagged differences		First + lagged differences	
	OECD	Non-OECD	OECD	Non-OECD	OECD	Non-OECD
ΔLog of latency (ΔlnLatency)	0.004 (0.012)	−0.007 (0.009)			0.02 (0.016)	−0.01 (0.011)
ΔLog of latency (ΔlnLatency) (t−1)			−0.03*** (0.010)	−0.009 (0.008)	−0.03*** (0.010)	−0.01 (0.008)
ΔLog of labour services (ΔlnLS)	−0.14 (0.230)	−0.32*** (0.119)	−0.14 (0.274)	−0.28** (0.134)	−0.12 (0.281)	−0.28** (0.134)
ΔLog of capital services (ΔlnK)	−0.29 (0.233)	0.08 (0.158)	−0.31 (0.250)	0.07 (0.181)	−0.31 (0.251)	0.07 (0.181)
Constant	0.014* (0.008)	−0.018 (0.012)	0.0006 (0.006)	−0.02 (0.014)	0.005 (0.008)	−0.025 (0.015)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.31	0.05	0.33	0.06	0.33	0.06
Number of observations	266	644	228	552	228	552

Note: The estimates are based on pooled Ordinary Least Squares (OLS). Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Latency data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021.

In Table 6, the lagged change in the log of latency is introduced for OECD and non-OECD countries. The lagged change in the log of latency is still insignificant for non-OECD countries, but highly significant for OECD countries at the one percent level. The results suggest that a 10 percentage points decrease in the growth of latency in period *t*-1 is associated with a 0.3 percentage points increase in TFP growth in OECD countries. When both the change in the log of latency and its lag are introduced in the regression analysis, the results for the lagged variable remain highly significant for OECD countries. Moreover, based on an F-test, it is possible to reject the hypothesis that both the first differences and the lagged differences are jointly equal to zero at the 1 percent level.

Robustness

Latency is not the only capability of a mobile broadband network that may be important for productivity in the economy. There is, for example, evidence that the speed in fixed broadband is important for economic development (Kongaut & Bohlin, 2014; Briglauer & Gugler, 2019). Moreover, there is also evidence of a lagged effect from mobile broadband speed on labour productivity (Edquist, 2022). In order to test the robustness of the results, the change in log of speed is introduced as an independent control variable. In addition, machine learning and IoT may primarily impact automation in manufacturing. Therefore, a control variable, measuring the size of manufacturing (in percent of GDP), is also introduced.

Table 7. Regressions of the relationship between TFP growth and the change in the log and lagged log of latency

	Dependent variable: TFP growth (ΔlnTFP)					
	First differences		**Lagged differences**		**First + lagged differences**	
	OECD	**Non-OECD**	**OECD**	**Non-OECD**	**OECD**	**Non-OECD**
ΔLog of latency (ΔlnLatency)	−0.0001 (0.014)	0.006 (0.006)			0.01 (0.019)	−0.0008 (0.007)
ΔLog of latency (ΔlnLatency) (t−1)			−0.03*** (0.012)	−0.003 (0.005)	−0.03*** (0.012)	−0.003 (0.005)
ΔLog of labour services (ΔlnLS)	−0.14 (0.229)	−0.44*** (0.074)	−0.11 (0.259)	−0.42*** (0.066)	−0.10 (0.268)	−0.42*** (0.066)
ΔLog of capital services (ΔlnK)	−0.29 (0.235)	−0.14** (0.066)	−0.32 (0.263)	−0.14** (0.069)	−0.32 (0.263)	−0.14** (0.069)
ΔLog of download speed (ΔlnSpeed)	−0.005 (0.006)	−0.007 (0.007)	−0.006 (0.007)	−0.008 (0.010)	−0.004 (0.009)	−0.008 (0.010)
ΔManufacturing size in (% of GDP) (ΔMfg)	0.0003 (0.0005)	0.001 (0.003)	−0.001 (0.003)	0.001 (0.003)	−0.001 (0.003)	0.001 (0.003)
Constant	0.02* (0.008)	−0.01* (0.007)	0.001 (0.006)	0.006 (0.008)	0.004 (0.008)	0.006 (0.008)
Year dummies	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.33	0.14	0.35	0.14	0.35	0.14
Number of observations	252	546	216	468	216	468

Note: The estimates are based on pooled Ordinary Least Squares (OLS). Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Latency and download speed data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021.

Table 7 shows that the lagged latency variable remains robust for OECD countries once the change in the log of speed and the change in the size of manufacturing are included as control

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variables. When we include both the change in log of latency and its lag, the lagged variable remains highly significant. Based on an F-test, it is possible to reject the hypothesis that both variables are jointly equal to zero at the 5% significance level.

So far countries have been divided into OECD and non-OECD countries, where OECD countries are based on the members of the OECD, i.e., some of the most industrialised countries in the world. However, countries could also be grouped based on income level. Thus, to further test the robustness of our findings, the sample is split into four different country groups. The World Bank (2023b) provides a classification of different countries based on income. The country groups are as follows in terms of GNI per capita in 2022: low income, $1,085 or less; lower middle income, $1,086 to $4,255; upper middle income, $4,256 to $13,205; and high income, $13,206 or more. Table 8 shows that there is no significant relationship between the lagged log change of latency and TFP growth for any of the country groups. Thus, it appears that the significant relationship only holds for OECD countries.

Simultaneity

One general problem with studies investigating the impact from ICT on productivity is simultaneity. Simultaneity implies that latency can be both a driver and a result from increased TFP growth. It is not unlikely that countries that achieve higher TFP growth also are able to invest more in mobile broadband networks and thus reduce latency. One approach to deal with simultaneity is to use instrumental variables that are correlated with the explanatory variables but not with the error term (Czernich *et al.*, 2011). However, it has not been possible to find valid instruments for mobile broadband latency.

Another approach is to use lagged variables as instruments. However, this method has been criticised by Reed (2015), who finds that it is not possible to escape simultaneity bias. A third method would be to use lagged values in 2SLS and GMM estimations. According to Reed (2015), this would only work if the lagged variables used do not themselves belong to the respective estimation equation and if they are sufficiently correlated with the simultaneously determined explanatory variable, i.e., latency. Based on earlier findings on the impact of ICT (Basu & Fernald, 2007; Brynjolfsson & Hitt, 2003), the lagged variable of latency belongs to the estimation equation. Thus, the method to correct for simultaneity is not attempted.

Table 8. Regressions of the relationship between TFP growth and the change in the log and lagged log of latency

First differences

	Dependent variable: TFP growth (ΔlnTFP)			
	First differences			
	Low-Income	Lower Middle-Income	Upper Middle-Income	High-Income
ΔLog of latency (ΔlnLatency)	0.004 (0.006)	0.001 (0.010)	0.02* (0.011)	0.01 (0.015)
ΔLog of latency (ΔlnLatency) (t-1)				
ΔLog of labour services (ΔlnLS)	0.33 (0.382)	−0.51 (0.375)	−0.39*** (0.132)	−0.33*** (0.067)
ΔLog of capital services (ΔlnK)	−0.21 (0.127)	0.03 (0.114)	−0.21 (0.198)	−0.52*** (0.109)
ΔLog of download speed (ΔlnSpeed)	0.002 (0.008)	0.002 (0.003)	−0.03 (0.012)	−0.01* (0.006)
ΔManufacturing size in (% of GDP) (ΔMfg)	0.002 (0.004)	0.004 (0.004)	−0.0006 (0.003)	−0.002 (0.002)
Constant	0.02 (0.014)	0.002 (0.010)	0.03 (0.014)	0.03 (0.007)
Year dummies	Yes	Yes	Yes	Yes
R^2	0.22	0.12	0.18	0,46
Number of observations	70	182	231	315

Lagged differences

	Dependent variable: TFP growth (ΔlnTFP)			
	Lagged differences			
	Low-Income	Lower Middle-Income	Upper Middle-Income	High-Income
ΔLog of latency (ΔlnLatency)				
ΔLog of latency (ΔlnLatency) (t-1)	0.001 (0.009)	0.004 (0.008)	0.004 (0.010)	−0.02 (0.018)
ΔLog of labour services (ΔlnLS)	0.30 (0.442)	−0.65 (0.464)	−0.24* (0.137)	−0.33*** (0.064)
ΔLog of capital services (ΔlnK)	−0.20 (0.143)	−0.003 (0.131)	−0.12 (0.193)	−0.58*** (0.116)
ΔLog of download speed (ΔlnSpeed)	0.001 (0.008)	0.009 (0.005)	−0.04* (0.018)	−0.02** (0.007)
ΔManufacturing size in (% of GDP) (ΔMfg)	0.001 (0.004)	0.004 (0.005)	−0.0002 (0.003)	−0.009*** (0.003)
Constant	0.004 (0.012)	−0.001 (0.012)	0.02 (0.014)	0.01 (0.008)
Year dummies	Yes	Yes	Yes	Yes
R^2	0.20	0.13	0.17	0.50
Number of observations	60	156	198	270

First + lagged differences

	Dependent variable: TFP growth (ΔlnTFP)			
	First + lagged differences			
	Low-Income	Lower Middle-Income	Upper Middle-Income	High-Income
ΔLog of latency (ΔlnLatency)	−0.0008 (0.007)	−0.004 (0.008)	0.03* (0.014)	0.03 (0.023)
ΔLog of latency (ΔlnLatency) (t-1)	0.002 (0.009)	0.004 (0.008)	0.009 (0.009)	−0.02 (0.017)
ΔLog of labour services (ΔlnLS)	0.30 (0.482)	−0.65 (0.460)	−0.22 (0.141)	−0.34*** (0.065)
ΔLog of capital services (ΔlnK)	−0.20 (0.149)	−0.004 (0.131)	−0.12 (0.189)	−0.58*** (0.116)

	Dependent variable: TFP growth (ΔlnTFP)			
	First + lagged differences			
	Low-Income	Lower Middle-Income	Upper Middle-Income	High-Income
ΔLog of download speed (ΔlnSpeed)	0.0005 (0.011)	0.008 (0.006)	−0.03* (0.016)	−0.01* (0.007)
ΔManufacturing size in (% of GDP) (ΔMfg)	0.001 (0.004)	0.004 (0.005)	0.001 (0.003)	−0.009*** (0.003)
Constant	0.004 (0.012)	−0.002 (0.013)	0.03* (0.018)	0.02* (0.009)
Year dummies	Yes	Yes	Yes	Yes
R^2	0.20	0.13	0.18	0.51
Number of observations	60	156	198	270

Note: The estimates are based on pooled Ordinary Least Squares (OLS). Cluster robust standard errors are presented in parentheses. ***, **, * indicate statistical significance at the 1%, 5% and 10% levels, respectively. Venezuela is included in the total sample, but it has been excluded when the sample is divided into different income classifications because it has not been classified by the World Bank (2023). Latency and download speed data based on analysis by Ericsson of Ookla® Speedtest Intelligence® data for 2014–2021. The country groups are as follows in terms of GNI per capita in 2022: low income, $1,085 or less; lower middle income, $1,086 to $4,255; upper middle income, $4,256 to $13,205; and high income, $13,206 or more.

Discussion of Results

There is a broad literature on the economic impact of ICT (e.g., Bertschek *et al.*, 2015; Vu *et al.*, 2020; Oliner & Sichel, 2000; Gordon, 2000; Jorgenson *et al.*, 2008; Van Ark *et al.*, 2008). The findings of this paper add knowledge to the literature by showing that there is an association between the lagged change of latency in the mobile broadband network and TFP growth in OECD countries. While the economic impact of fixed and mobile broadband and the speed in the networks have been investigated before (Rohman & Bohlin, 2012; Kongaut & Bohlin, 2014; Briglauer & Gugler, 2019; Edquist, 2022), there is a lack of knowledge about the impact of latency.

As pointed out in the literature section, the GPT literature suggests that there might be a lagged effect from new technology. The most famous example is the Nobel Laureate Robert Solow observing, in the 1980s, that the computer age could be seen everywhere but in the productivity statistics. One explanation for a delayed effect might be that applications that need lower latency also require organizational restructuring (Helpman, 1998). An additional explanation might be that innovational complementarities, such as new applications that require low latency, are necessary before productivity gains are achieved. This implies that there might be a lagged effect from latency.

The lagged specification used in this paper implies that the change of the dependent variable between two points in time is a function of the specified difference of the independent variable between the preceding points in time (Leszczensky & Wolbring, 2019). This implies that the model with a lagged change in the log of latency is only appropriate if the lags in the panel data match the real-world causal lags in the process under study (Vaisey & Miles, 2017). However, according to the literature on General Purpose Technologies, there is reason to believe that latency would have a lagged effect on productivity, as it takes time for new technology to affect productivity growth (David, 1990; Brynjolfsson & Hitt, 2003).

The findings that the lagged variable is only significant for OECD countries is also of interest. One possible explanation could be that OECD countries have reached a higher maturity in digitalisation and automation in production processes and thus are able to take advantage of the benefits of lower latency. One indicator of digital maturity that is important from a latency perspective is IoT penetration, i.e., IoT connections per 100 inhabitants. According to Edquist et al. (2021), IoT connections have increased considerably during the last decade worldwide. IoT devices that are used for personal and business tasks are dependent on fast transfer of information, which implies that latency plays a vital role in the smooth operations of these devices (Siddiqi *et al.*, 2019).

Figure 2 shows that IoT connections per 100 inhabitants in OECD and non-OECD countries are quite similar. However, if China is excluded, the difference between OECD and non-OECD countries increases considerably. In 2023, OECD countries had 45 IoT connections per 100 inhabitants, while the corresponding figure for non-OECD countries, excluding China, was only 5. This is a clear indication that OECD countries have reached a higher maturity in digitalisation compared to non-OECD countries excluding China. China is an exception with high IoT connections per 100 inhabitants, which shows the enormous digitalisation that has taken place in the Chinese economy since 2010. However, China only has a minor impact in the econometric analysis since all countries that are included have the same weight.

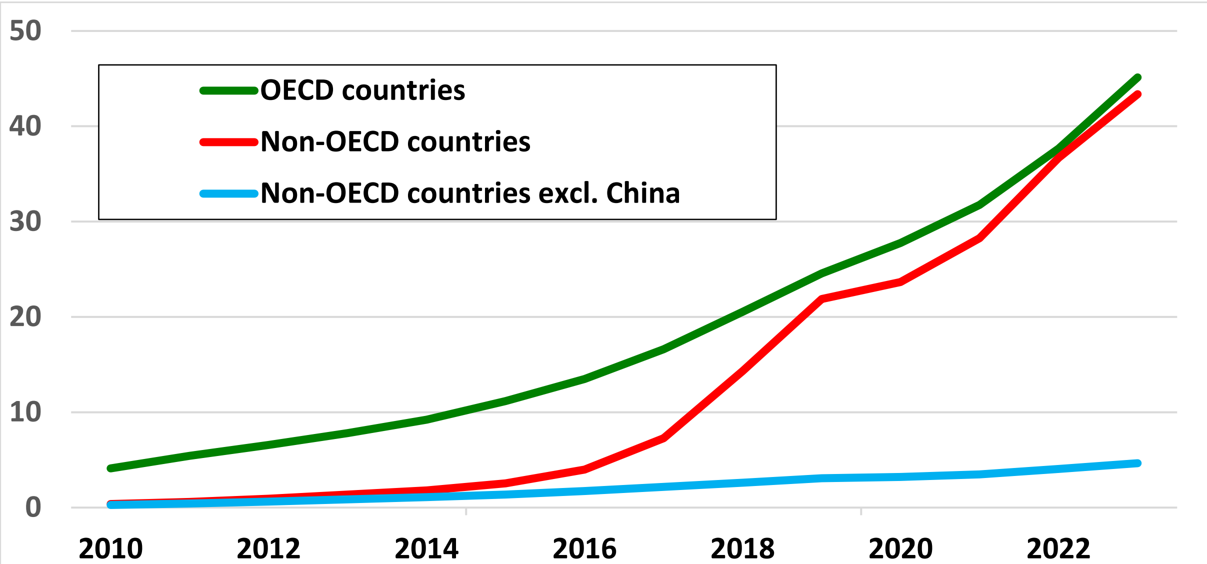

Figure 2. IoT devices per 100 inhabitants in OECD and non-OECD countries (including and excluding China) 2010–2023. (Source: GSMA, 2024). **Note: The Figure is based on data for 169 countries.**

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Conclusions

This paper has investigated the relationship between the log change in mobile broadband latency and TFP growth based on data for 130 countries. It finds no correlation between the log change of mobile broadband latency and TFP growth for the total sample. However, there is a strong negative relationship (at the one percent level) between the log change in the one-year lag of latency and TFP growth in OECD countries. Thus, a 10 percentage points decrease in the growth of latency in period t-1 is associated with an increase of 0.3 percentage points in TFP growth in OECD countries.

The lagged specification implies that the change of the dependent variable between two points in time is a function of the specified difference of the independent variable between the preceding points in time (Leszczensky & Wolbring, 2019). This implies that the model with a lagged change in the log of latency is only appropriate if the lags in the panel data match the real-world causal lags in the process under study (Vaisey & Miles, 2017). However, according to the literature on General Purpose Technologies, there is reason to believe that latency would have a lagged effect on productivity, as it takes time for new technology to affect productivity growth (David 1990; Brynjolfsson & Hitt, 2003).

The findings that the lagged variable is only significant for OECD countries is also of interest. It suggests that it is primarily OECD countries that are able to take advantage of the benefits of lower latency. Figure 2 clearly shows that OECD countries have a much higher IoT concentration, measured as IoT connections per 100 inhabitants, compared to non-OECD countries excluding China. Thus, one possible explanation could be that OECD countries have reached a higher maturity in digitalisation and automation in production processes and thus are able to take advantage of the benefits of lower latency.

These findings also provide some hope for future productivity development. There appear to be continued possibilities of increased productivity by investing in cellular networks and ICT technology. Thus, policy makers in OECD countries should continue to facilitate investment in cellular networks without distorting market competition, which will hopefully lead to better capabilities in the networks and higher productivity in the OECD economies. In contrast, policy makers in non-OECD countries need to establish a further understanding of why the lagged change of latency may not be correlated with productivity growth in their respective economies. Thus, further research is necessary in order to understand why lower latency is not associated with TFP growth in non-OECD countries. Possible explanations might be that non-OECD countries have not made large investments in IoT infrastructure, that additional investment in intangible assets, such as R&D and vocational training, are needed, or simply that the structure of non-OECD countries is completely different from the structure of OECD countries. Based on the findings, policy makers in non-OECD countries should proceed to develop a broadband strategy that best fits their respective economies.

Finally, this paper has extended the analysis of the association between lagged change in latency and TFP growth. An additional area for future research would be to investigate how lower latency improves productivity in different industries and companies. This paper is limited to only establishing that there is a negative association between one-year lag of latency and TFP growth at the country level, but not what is driving this development. Moreover, it remains to be seen how continued investment in mobile infrastructure will affect productivity growth as new use cases and technologies, such as Artificial Intelligence, become available at a large scale.

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