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ICT development and productivity of transport infrastructure

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ICT Development and Productivity of Transport Infrastructure

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Abstract

This paper examines the impact of ICT network on productivity contribution of transportation infrastructure. Using dynamic panel data of OECD member countries, the paper finds that there exists significant complementarity between ICT network and transportation infrastructure. The network effect of motorway infrastructure in OECD countries tends to accelerate when the ICT network grows beyond a certain threshold level.

Keywords: Intelligent Transport System, ICT convergence, productivity growth, complementarity.
JEL classification: O47, O38

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1.0 Introduction

Public investment in economic infrastructure such as transport and digital communications is a key for economic growth[1]. Infrastructure is not only used as an essential input in the other sectors thereby contributing directly to GDP, but enables more efficient use of ordinary factors of production by reducing transaction costs. Such spill-over effects from accelerating network economies of infrastructure development deserve serious attention. Without proper government intervention, the market force can hardly achieve socially efficient level of investment.

Investment in infrastructure creates long-lived highly risky assets with huge sunk costs and network economies. Functional complementarities among different types of infrastructure give rise to additional difficulties in optimal design of infrastructure investments. Considering the fact that more than 60 percent of the infrastructure investment is carried by the sub-national governments of developed countries,[2] the national governments have to design and implement cooperative investment schemes between levels of government to maximize the potential benefits arising from network and complementary effects across sectors.[3]

The main driving force of network economies and complementary effects arise from application of Information and Communication Technology (ICT) to many important components of infrastructures including motorway, railroad, gas and electricity.[4] Thanks to

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[1] For extensive discussion on the role of infrastructure in economic development, see World Bank (2008).

[2] OECD National Accounts 2012. According to Ahrend, Curto-Grau, and Vammalle (2013), debt of sub-national governments in OECD area increased on average from 10 percent of GDP in 2007 to 13 percent in 2010.

[3] It has been controversial in the literature whether there exists a positive causal relationship between investment in public infrastructures and economic growth. See for example, Slovoda and Yao(2008) and Crescenzi and Rodríguez-Pose (2012)

[4] According to Bloomberg New Energy Finance (BNEF 2013), global investment in smart grid technology was 13.9 billion dollars in 2012. Presidential Council on National Competitiveness in Korea noted that most of the developed countries targeted Intelligent Transportation System as a national development strategy. The United States passed the Intermodal Surface

the sensor technology and communication software, the converged infrastructure becomes not only 'smart' but increasingly complementary to each other. In fact, the network effects of infrastructure tend to be accelerating as the broadband infrastructure for digital communications grows beyond a critical mass. Despite growing importance of convergence effects in real world, however, there has been little empirical literature that examines the contribution of ICT network to infrastructure development. The paper examines the nature of complementary effects between transportation and ICT network infrastructure by empirically estimating the role of ICT network in productivity impact of motorway infrastructure.

The contribution of transport infrastructure to Total Factor Productivity (TFP) growth has been examined by Na, Han, and Yoon (2013).[5] By estimating the productivity effects of motorway infrastructure across OECD countries, they show that the productivity contribution of motorway tends to increase as the motorway extends over time. They find that an accelerating network effect prevails when the motorway grows beyond the threshold level.

Na and Yoon (2015) examines the role of ICT network in productivity contribution of motorway. Following Röller and Waverman (2001), they trace the effect of ICT network on motorway contribution to Total Factor Productivity (TFP) growth by varying the network size. They attempt to prove existence of a critical mass of broadband penetration rate beyond which motorway contribution to macroeconomic productivity accelerates. However, their regression framework does not allow precise estimation of complementary linkage effects between two types of infrastructure.

This paper investigates the complementary effects of ICT and motorway infrastructure by

Transportation Efficiency Act in 1991, and chalked out a plan to invest more than 20 billion US dollars until 2020. The European Union proposed an integrated ITS through a trans-European transport network.

[5] For empirical investigation of the role of transport infrastructure, see for example, Aschauer (1989); Sim and Yoon (2001); Kunihisa and Kaiyama (1998); Canning and Bennathan (2000); Calderon and Serven (2003); Cantos et al. (2005); and Égert et al. (2009)

allowing a more general nonlinear relationship than in Na and Yoon (2015). Although the dynamism of the market makes it difficult to quantify network effects and scale economies, this paper manages to estimate the threshold level of ICT infrastructure by focusing on the effects of infrastructure on TFP growth. Using the dynamic panel data of OECD member countries, the paper examines complementary linkage effects between two types of infrastructure.

The paper begins by examining the comparative trend of investments in ICT network and motorway infrastructure. The main testable hypothesis on the role of critical mass and complementary effects of infrastructure is introduced. Empirical estimation results for the threshold level of ICT network and complementary linkage effects are explained. Concluding remarks follow with brief policy implications for infrastructure investment strategy.

2.0 ICT and Transport Infrastructure

ICT has been successfully converged to the vehicle industry and road system in recent decades. The convergence of ICT and transportation technology has led to the development of the so-called Intelligent Transportation System (ITS). ICT produces cost-effective systems for collecting data for monitoring and positioning, and systems and protocols for communicating data between traffic control centers and to and from vehicles. ICT ensures accuracy and timeliness of data transmission to relieve congestion and reduce fatality (Black and Geenhuizen, 2006). In other words, ICT helps improve quality and safety of mobility, which eventually appears as an increase in Total Factor Productivity (TFP) of transport infrastructure in the growth accounting.

2.1 Communication architecture components in ITS[6]

Every ITS service depends on the availability of an ICT backbone and enabling systems that constitute the core of ICT infrastructure, laying the foundation for all services. According to US DOT (2004), ITS consists of four components, vehicle, roadside (traffic), personal (traveler), and central (center), all of which are connected through wide-area wireless communications, wire-line communications, vehicle-to-vehicle (V2V) communications, and dedicated short-range communications (DSRC).

Vehicle is normally equipped with a module to communicate with other vehicles, roadside infrastructure and central system which includes for example a router and embedded PCs. The module allows access to Controller Area Network (CAN) and collection and process of date from other vehicles. Roadside infrastructure consists of variable message signs (VMSs), traffic lights and other equipment for communication. The roadside component plays a role of relay station through multi-hop communication, and offers information from the other roadside units and central system. The roadside component can be also connected to the Internet.

The personal component of ITS is a nomadic device. Personal navigator or mobile phone is often used. Personal devices can support cooperative ITS applications by communicating with other road users and roadside. The central component of ITS applications is a road operator which administers cooperative applications or services. An example of such component is a traffic management center which uses roadside units to inform the drivers about traffic status or accidents in a specific road network and suggests alternative routes. The central component collects information from individual vehicles and roadside units and forward back processed information.

[6] For detailed explanation of ITS communication architecture, see ETSI (2011) and US DOT (2004).

2.2 Infrastructure investments and productivity impact

In most developed countries, investments in both digital communications and motorway infrastructure have increased substantially during the recent decades (Na and Yoon, 2015). But their growth rates and correlation with productivity growth are not monotone. For expositional convenience, let's define the motorway capital by motorway length (km) per worker, and the broadband penetration rate by the number of broadband subscribers per 100 inhabitants.

Investments in ICT network and motorway capital in OECD member countries are compared for two bench mark years of 2000 and 2005 in Fig. 2 (a) and (b) respectively. The broadband penetration rate was generally low around the year 2000 except in Nordic countries in Europe, North America and the Republic of Korea. On the other hand, the growth rate of motor way capital was quite high in Finland, Japan, and United Kingdom in the early 2000s showing no significant correlation between two types of infrastructure investment.

The broadband penetration rate reached 60.5 percent on average in 2005. The early adopters of broadband infrastructure made relatively high sustained advance until 2005. In contrast to the year 2000, the growth rate of motorway capital turned relatively high in those countries with high broadband penetration rate. In fact the windowed correlation coefficient between two growth rates turned positive only after 2003 (Na and Yoon, 2015).

To examine the non-monotone character of correlation coefficients, let's group the OECD member countries into two categories. The High group is defined as a set of countries where the broadband penetration rate exceeds the OECD average rate in the year 2005. The remaining set of countries is classified as the Low group. Fig. 3 illustrates graphical relationship between TFP growth and motor way capital across countries that belong to each group. The productivity impact of motorway capital is more pronounced in the High group than in the Low group. Unless the broadband penetration ratio exceeds a certain threshold level, positive productivity impact of motorway infrastructure is not assured

For later references, let's examine transport efficiency index published by The World Bank which is called Logistics Performance Index (LPI).[7] LPI represents a weighted average index of six items that influence competitiveness of transportation service. Finland seems to have advanced high from 12th to 3rd rank thanks to her well-developed ICT infrastructure.[8] Finland marked high score in international shipping, transport capacity, and tracking and tracing, and ranked 3rd in overall competitiveness of transportation service out of 155 countries. Similarly, Denmark advanced from 16th to 6th rank. On the other hand, countries like Germany, Netherlands, the United Kingdom, and Japan did not gain relative competitiveness in transportation service.

Finally, an alternative measure of ICT network Internet bandwidth in Mbps (mega bit per second) is introduced for sensitivity analysis. Fig. 4 illustrates log of international Internet bandwidth against broadband penetration rate of ITU.[9] Both indicators move closely in tandem until the early 2000s. Since then the indicator of international Internet bandwidth increases more slowly than the number of subscribers. In the next section, both indicators are adopted for sensitivity analysis.

3.0 Econometric analysis of productivity growth

3.1 Model

[7] LPI is calculated for 150 countries in 2007, and 155 countries for 2010 and 2012. The index is weighted average of scores for the following six items: i) Customs: speed, simplicity and predictability of custom procedure; ii) Logistics Infrastructure: the level of infrastructure in harbor, railroad, motor road and ICT; iii) International shipments; iv) Logistics competence; v) Tracking and tracing; vi) Timeliness of transport service. LPIs of OECD member countries are listed in the Appendix A1.

[8] Singapore ranked first and Hong Kong-SAR-China ranked second in 2012 (World Bank 2012).

[9] International Internet bandwidth is measured as the sum of capacity of all Internet exchanges offering international bandwidth. We mean by International Bandwidth the maximum quantity of data transmission from a country to the rest of the world. See ITU World Telecommunication-ICT Indicator (2010).

The aggregate production function is postulated as $Y=A \cdot F(L, K)$, where Y stands for the GDP, A represents the TFP, and L and K denote labor and capital stock, respectively. It is assumed that TFP depends among others on the level of ICT network and motorway capital and is influenced by time- and country-specific economic effects. Let n and z respectively denote the level of ICT network and motorway capital. Let's define that two components of infrastructure, ICT network and motorway capital are *complementary in TFP growth* if $\frac{\partial^2 A}{\partial n \partial z} > 0$. According to UNECE (2012), ITS performance depends critically on the size and quality of ICT networks in the economy.[10] The intelligent transport services are possible only if the ICT network exceeds a minimum critical mass. This paper tests the hypothesis that there exists a threshold level of ICT network n_0 whch satisfies the following property;

$$\frac{\partial^2 A}{\partial n \partial z} = 0 \quad \text{for} \quad n \le n_0 \quad \text{and} \quad \frac{\partial^2 A}{\partial n \partial z} > 0 \quad \text{for} \quad n > n_0 \tag{1}$$

The base model for our estimation is specified as following.

$$ln\, TFP_{it} = \alpha_{i0} + \alpha_i t + g(n_{it-1}, ln\, z_{it-1}) + X_{it}\beta + \mu_t + u_{it} \tag{2}$$

where i and t represent the country and time period, respectively. In this model, α_{i0} is the country-specific level of the TFP, $\alpha_i t$ is the country-specific trend coefficient, z_{it-1} is lagged road infrastructure, n_{it-1} lagged ICT capital and μ_t is time-specific coefficient; $g(\cdot)$ denotes a non-linear functional relationship that describes the productivity impacts of motorway capital and ICT network, while X_{it} denotes a vector of control variables that

[10] According to UNECE (2012), the capability to deliver ITS services does not grow in a linear fashion with the augmentation of available technology, but for most ITS services a minimum critical mass is needed in order to perform a wide number of tasks.

include human capital, degree of congestion, and openness of the economy.[11] The error term u_{it} represents influence of various macro variables including unobservable factors, and is serially correlated over time. To control for country-specific trends and integrated errors, we propose a first-differenced dynamic panel model as follows:

$$\Delta \ln TFP_{it} = \alpha_i + \Delta g(n_{it-1}, \ln z_{it-1}) + \Delta X_{it}\beta + \sum_{j=1}^{p} \rho_j \Delta \ln TFP_{it-j} + \tau_t + \epsilon_t \quad (3)$$

where $\tau_t \equiv \Delta\mu_t, \epsilon_t \equiv \Delta u_t$.

We assume that ϵ_{it} is independent over time. In other words, given the past sequence of TFP growth rates, the current TFP growth rate depends on one-year lagged motorway capital and ICT network, global time effects, and unpredictable shocks. Using the dummy variables for a threshold level of ICT capital, the following nonlinear models can be estimated.

$$\Delta \ln TFP_{it} = \alpha_{it} + \gamma_0 \Delta \ln z_{it-1} + \gamma_1 D_{n>m} \Delta \ln z_{it-1} + \Delta X_{it}\beta + \epsilon_t \quad (4)$$

$$\Delta \ln TFP_{it} = \alpha_{it} + [\gamma_0 + \gamma_1 Max(0, n_{it-1} - m)] \Delta \ln z_{it-1} + \Delta X_{it}\beta + \epsilon_t \quad (5)$$

Equation (4) describes a discontinuous jump in TFP when the ICT network grows beyond a threshold level. Equation (5) represents a jump in the slope or marginal contribution to TFP of motorway capital. Na and Yoon (2015) examines the estimation results for the above specifications in detail. By varying *m* in both equations, one can arrive at the best possible estimator of a threshold level.

Alternatively a more intuitive way to motivate a nonlinear specification is possible. Using the dummy variables for the High group and Low group of countries that are classified according to the broadband penetration rate in the previous section, difference-in-differences

[11] Fernald (1999) presented a theoretical model for the relation between road capacity and motorway usage. If usage exceeds the road capacity, transportation cost tends to increase due to congestion. It is natural to treat a degree of congestion as a control variable.

(DID) method is adopted to derive the following specifications, Equation (6) for Low group and (7) for High group respectively.

$$\Delta \ln TFP_{it} = \alpha_i + (\gamma_0 + \gamma_1 D_{low})\Delta \ln z_{it-1} + \delta D_{low} + \Delta X_{it}\beta + \sum_{j=1}^{p} \rho_j \Delta \ln TFP_{it-j} + \tau_t + \epsilon_{it} \quad (6)$$

$$\Delta \ln TFP_{it} = \alpha_i + (\gamma_0 + \gamma_1 D_{high})\Delta \ln z_{it-1} + \delta D_{high} + \Delta X_{it}\beta + \sum_{j=1}^{p} \rho_j \Delta \ln TFP_{it-j} + \tau_t + \epsilon_{it} \quad (7)$$

The estimation results are shown in Table 3 and will be discussed shortly. Let us now introduce a more general approach to incorporate the possibility that the marginal contribution of motorway capital to productivity growth depends on the level of ICT network. The following models allows direct estimation of a threshold level.

$$\Delta \ln TFP_{it} = \alpha_i + (\gamma_0 + \gamma_1 n_{it-1} + \gamma_2 n_{it-1}^2)\Delta \ln z_{it-1} + \Delta X_{it}\beta + \sum_{j=1}^{p} \rho_j \Delta \ln TFP_{it-j} + \tau_t + \epsilon_{it} \quad (8)$$

The equation (8) is used to estimate the effect of ICT infrastructure on the productivity of motorway capital as following:

$$\frac{\Delta \ln TFP_{it}}{\Delta \ln z_{it-1}} = \widehat{\gamma_0} + \widehat{\gamma_1} n_{it-1} + \widehat{\gamma_2} n_{it-1}^2 \quad (9)$$

The direct productivity effect of motorway capital is represented as $\widehat{\gamma_0}$ while the complementary linkage effects of ICT network depends on $\widehat{\gamma_1}$ and $\widehat{\gamma_2}$, and their statistical significance.

The data for econometric analysis are collected from 21 OECD member countries for the period 1996-2006.[12] The motorway length (in km) per worker (z) and the number of vehicles

[12] The 21 sample countries includes Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, New Zealand, the Netherlands, Norway, Portugal, the Republic of Korea, Spain, Sweden, the Switzerland, the United

are calculated from the OECD Factbook (2008). The data on GDP, total capital stock, and number of workers are obtained from the OECD Economic Outlook (2012), and each country's information infrastructure (n_{it-1}) is measured by the number of broadband subscribers (per 100 inhabitants) reported in the ITU World Telecommunication-ICT Indicator (2010). The productivity contribution is measured in terms of a change in total factor productivity (TFP), available from the OECD productivity database.

Equations (6)-(8) indicate that the effect of motorway capital on TFP growth depends in general on ICT infrastructure and a set of control variables, $\Delta X_{it} = (\Delta S_{it}, Open_{it}, \Delta lnV_{it})$. The data for human capital (S_{it}),[13] are obtained from years of schooling for persons 25 years and over (Cohen and Soto, 2007), and congestion is measured by the proxy variable V_{it}, which measures the ratio of the number of vehicles over population. Degree of openness ($Open_{it}$) is measured as the ratio of trade volume to GDP (OECD Stat Extracts).[14] The descriptive statistics of major variables are given in Table 1.

3.2 Empirical findings

Table 2 presents the estimation results for Equations (6), (7) and (8). Both the fixed-effect and dynamic panel data estimation results are summarized. The first-order autoregressive process (AR (1)) is adopted for dynamic panel data estimation.[15] In each estimation model, lnz_{it-1} is additionally controlled to allow for the possible dependence of motorway productivity on the level of motorway capital.

In the DID estimation model for countries with low level of broadband penetration rate, the productivity effect of motorway capital is relatively low with 0.003 (0.048-0.045) while for

Kingdom, and the United States.

[13] For human capital, we consider the Mincerean form (see Mincer 1974; Bils and Klenow 2000; and Krueger and Lindahl 2001) which, in its simplest form, specifies the logarithm of human capital as a linear function of years of schooling.

[14] Following Harrison (1996), we assume that openness is specified to influence TFP growth, not the TFP level.

[15] See Arellano and Bond (1991) and Arellano and Bover (1995).

high group of countries, it is quite high with 0.048. Since DID estimation depends on the exogenously specified threshold level of broadband infrastructure, discontinuous jump in the estimated productivity effect is likely to be overestimated. Equation (8) can be estimated without prior specification of threshold level. Model 3 adopts fixed effect (Least-Squares Dummy Variables, LSDV) estimation and is compared with difference GMM estimation results.[16] In Model 4, the estimated coefficients (γ_2) of the role of ICT infrastructure in the productivity impact of motorway capital is found to be statistically significant and positive. The estimation result allows us to draw meaningful implications for the network effects of infrastructure investment.

Based on estimation results for Model 4, the threshold level of broadband penetration rate can be calculated as 0.61 and is indicated in Fig. 5. When n_{it-1} is less than 0.61, the effect of growth of motorway capital on TFP growth is negative.[17] On the other hand when n_{it-1} exceeds 0.61, ICT infrastructure complements motorway capital and produces a statistically significant additional beneficial effect.

For example, in a country where the broadband penetration ratio was 0.7 in the previous period, the marginal effect of growth of motorway capital on TFP growth becomes 0.012($\widehat{\gamma_0}$)-0.244($\widehat{\gamma_1}$)×0.70+0.365($\widehat{\gamma_2}$)×0.49=0.02. If the broadband penetration rate exceeds 80 percent, the effect of growth of motorway capital on TFP growth becomes 0.012($\widehat{\gamma_0}$)-0.244($\widehat{\gamma_1}$)×0.80+0.365($\widehat{\gamma_2}$)×0.64=0.05 and is more than doubled than when the broadband penetration rate is 70 percent. In other words, when the ICT infrastructure measured in terms of the broadband penetration rate exceeds a certain threshold level, it complements motorway

[16] Hausman test reveals that p-value is close to zero. We also considered the estimations using Arellano and Bover's (1995) system GMM for solving the weak instrumental variables problem. The main results are almost the same.

[17] Even in the case where the broadband penetration rate is less than the threshold level, the monotonically increasing relationship between TFP level and motorway capital is maintained. The rate of increases however becomes negative in the region where the broadband infrastructure falls short of the threshold level.

capital in TFP growth. Models 5 and 6 present the estimation results for international Internet bandwidth. Again, there exists strong complementarity between ICT and motorway infrastructure when the ICT infrastructure grows beyond a certain threshold level.

The effect of human capital (ΔS_{it}) is approximately 0.1, which is consistent with the findings of various human capital studies (Cohen and Soto, 2007). The effect of openness ($Open_{it}$) is approximately 0.06-0.1, which is close to 0.08 obtained by Harrison (1996). The road usage (ΔlnV_{it}) turns out to be statistically insignificant.

The robustness of the estimation results on the role of ICT and motorway infrastructure can be examined by estimating the effect of infrastructure on average labor productivity (ALP) growth. Given the constant returns to scale (CRS) production function, $Y = AF(L, K)$, we have $lny_{it} = lnA\{g(n_{it-1}, ln\, z_{it-1})\} + \theta\, ln\, k_{it}$, where $y_{it} = Y_{it}/L_{it}$, $k_{it} = K_{it}/L_{it}$, and θ is the share of capital.[18] Then the following equation can be obtained:

$$\Delta\, ln\, y_{it} = \alpha_i + (\gamma_0 + \gamma_1 n_{it-1} + \gamma_2 n_{it-1}^2)\Delta\, ln\, z_{it-1} + \theta \Delta lnk_{it} + \Delta X_{it}\beta + \sum_{j=1}^{p} \rho_j\, \Delta\, ln\, y_{it-j} + \tau_t + \epsilon_{it} \quad (10)$$

The estimation results for Equation (10) are reported in the appendix A3. The estimated coefficients and statistical significance remain almost the same as the results for Equation (8). The complementary network effects are found in both models.

Our estimation results confirm the validity of necessary conditions for positive productivity impacts of ITS (UNECE, 2012). The convergence of ICT and transportation technology enforces positive spillover effects of motorway infrastructure on productivity growth only when the ICT infrastructure grows beyond a certain threshold level. It is interesting

[18] The annual PPP-adjusted GDP (Y), total capital stock (K), and total employment (L) are taken from the OECD Economic Outlook (2012) database. The data for total capital stock for the Republic of Korea are taken from Pyo, Jung, and Cho (2007).

to note that in many OECD member countries, the ICT infrastructure has grown beyond the threshold level. Our data reveal that after 2004, the broadband penetration ration began to exceed 61 percent in 13 countries, including the Republic of Korea, the United States, and Japan.[19]

Finally the recent acceleration of LPI for the period of 2007-2012 is compared with estimated productivity effect of motorway as of 2006 in Model 4. The estimated productivity effects is given as $\frac{\Delta \ln TFP_{it}}{\Delta \ln z_{it-1}} = \widehat{\gamma_0} + \widehat{\gamma_1} n_{it-1} + \widehat{\gamma_2} n_{it-1}^2$. As Fig. 6 illustrates, two indicators for growth of transport competitiveness follows the similar pattern across countries.[20]

4.0 Concluding remarks

This study presents a simplified analysis of complementary linkage and scale effects between transportation and ICT infrastructures by showing empirically that the contribution of motorway infrastructure to productivity growth increases over time only if the ICT infrastructure grows beyond a certain threshold level. Although our empirical analysis is carried out for OECD member countries, the pattern of complementary linkage effects may appear also in the developing countries as well since convergence takes place rapidly in the global context.

Effective transportation system demands effective communication between infrastructure and vehicles, collaborative vehicle data platform for traffic flow and continuous monitoring of vehicle conditions. Tens of millions of cars across the globe are likely to have internet access

[19] They are Canada, Denmark, Finland, Germany, Japan, Netherlands, New Zealand, Norway, the Republic of Korea, Sweden, Switzerland, United Kingdom, and United States.

[20] The correlation coefficient between the magnitude of LPI acceleration in the recent period and the estimated productivity effects is 0.64. Acceleration pattern of LPI across countries reasonable well reflects estimated productivity growth of motorway infrastructure. Two indicators are not consistent in Belgium, France, Italy, Netherlands, Portugal, Spain, and Sweden.

and enjoy the benefits of connected cars in the near future. The market dynamism is generally nonlinear and difficult to understand for policy makers. This paper provides an empirical insight into the nature of the initial fixed social costs of building intelligent transport system by illustrating the existence of threshold level of ICT network.

Although the share of motorway in transportation service exceeds more than 70 percent in European countries, and more than 50 percent in OECD countries on average,[21] it will be certainly interesting to extend the current research to other transportation infrastructure including railway and ocean transportation.

Finally the paper focused on the role of infrastructure on TFP growth. A more general model to investigate complementary relationship among different components of infrastructure will require an extensive econometric analysis of the production structure of the economy as a whole and is not attempted in this paper.

[21] The share of road in freight transportation tends to increase in OECD countries, especially in European continent. International Transport Forum database (2011).

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Table 1 Descriptive statistics

Variables	Obs.	Mean	Std. Dev.	Max.	Min.
$\Delta \ln TFP_{it}$	310	0.011	0.014	0.076	-0.069
$\Delta \ln z_{it-1}$	287	0.033	0.111	1.389	-0.328
ΔS_{it}	320	0.074	0.034	0.169	0.009
$Open_{it}$	357	0.347	0.162	0.924	0.081
$\Delta \ln V_{it}$	320	0.015	0.032	0.177	-0.210
n_{it-1}	356	0.245	0.259	0.860	0.000
$lnnb_{it-1}$	164	9.357	3.379	14.393	-4.240
$\Delta \ln y_{it}$	335	0.017	0.015	0.074	-0.028
$\Delta \ln k_{it}$	302	0.029	0.020	0.119	-0.160

Note: $lnnb_{it-1}$denotes lagged log value of international Internet bandwidth (Mbps).

Table 2 Estimation results (TFP growth)

$\Delta lnTFP_{it}$	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
	Diff. GMM	Diff. GMM	Fixed effect	Diff. GMM	Fixed effect	Diff. GMM
$\Delta lnTFP_{it-1}$	0.040 (0.060)	0.040 (0.060)	0.044 (0.067)	0.044 (0.062)	-0.141 (0.111)	-0.141 (0.100)
Δlnz_{it-1}	0.048* (0.027)	0.003* (0.004)	0.012* (0.006)	0.012** (0.006)	0.221* (0.122)	0.221** (0.109)
low	-0.003 (0.003)					
$high$		0.003 (0.003)				
$low\Delta lnz_{it-1}$	-0.045* (0.025)					
$high\Delta lnz_{it-1}$		0.045* (0.025)				
$n_{it-1}\Delta lnz_{it-1}$			-0.244*** (0.067)	-0.244*** (0.063)		
$n_{it-1}^2\Delta lnz_{it-1}$			0.365** (0.128)	0.365*** (0.119)		
$lnnb_{it-1}\Delta lnz_{it-1}$					-0.061* (0.031)	-0.061** (0.028)
$lnnb_{it-1}^2\Delta lnz_{it-1}$					0.004* (0.002)	0.004** (0.002)
ΔS_{it}	0.104** (0.053)	0.104** (0.053)	0.094 (0.058)	0.094* (0.054)	0.101 (0.064)	0.101* (0.057)
$Open_{it}$	0.057*** (0.018)	0.057*** (0.018)	0.069*** (0.022)	0.069*** (0.021)	0.113*** (0.028)	0.113*** (0.025)
ΔlnV_{it}	0.007 (0.024)	0.007 (0.024)	0.013 (0.027)	0.013 (0.025)	-0.048 (0.047)	-0.048 (0.043)
lnz_{it-1}	-0.010** (0.005)	-0.010** (0.005)	-0.006 (0.006)	-0.006 (0.006)	-0.010 (0.012)	-0.010 (0.011)
Constant	-0.091** (0.043)	-0.094** (0.043)	-0.066 (0.055)	-0.066 (0.051)	-0.117 (0.098)	-0.117 (0.090)
AR(1) p-value	0.0003	0.0003		0.0004		0.0024
AR(2) p-value	0.4222	0.4222		0.2550		0.1984
Sargan p-value	0.3657	0.3657		0.3598		0.2820
R^2			0.248		0.311	
Obs.	231	231	250	231	139	120

*, **, ***: Significant at the 10 percent, 5 percent, and 1 percent levels, respectively.

Note 1: The robust standard errors for panel data are reported in parentheses.

Note 2: Time dummies are included, but their results are not reported.

Note 3: In Difference GMM, every explanatory variable is treated as a predetermined variable except ΔlnV_{it} as endogenous variable. Arellano and Bond's (1991) specification test in Difference GMM rejects AR(1) but accepts AR(2). According to the Sargan test, Models 1, 2, 4 and 6 satisfy the conditions for estimation of dynamic panel data.

Fig. 1 Communication architecture components in ITS

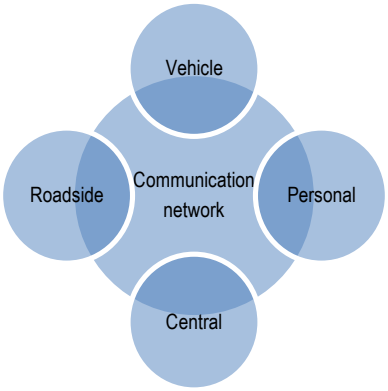
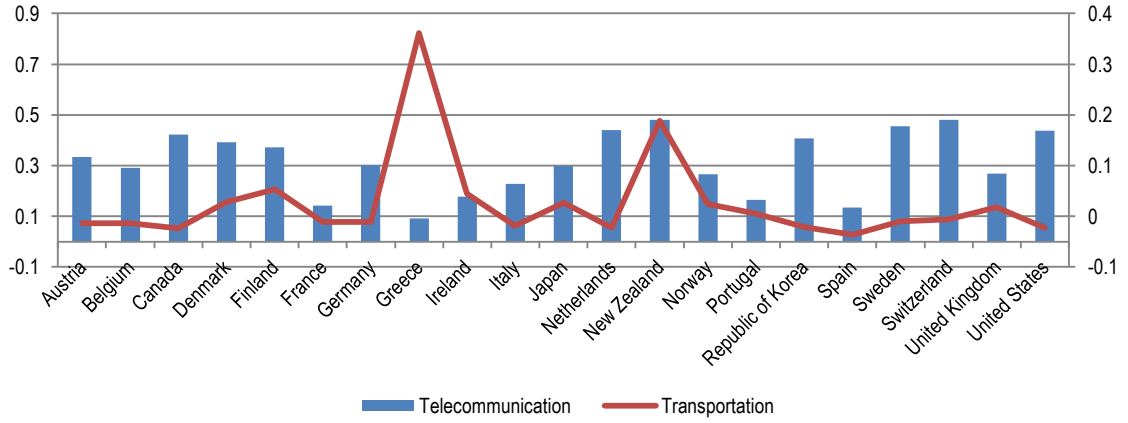
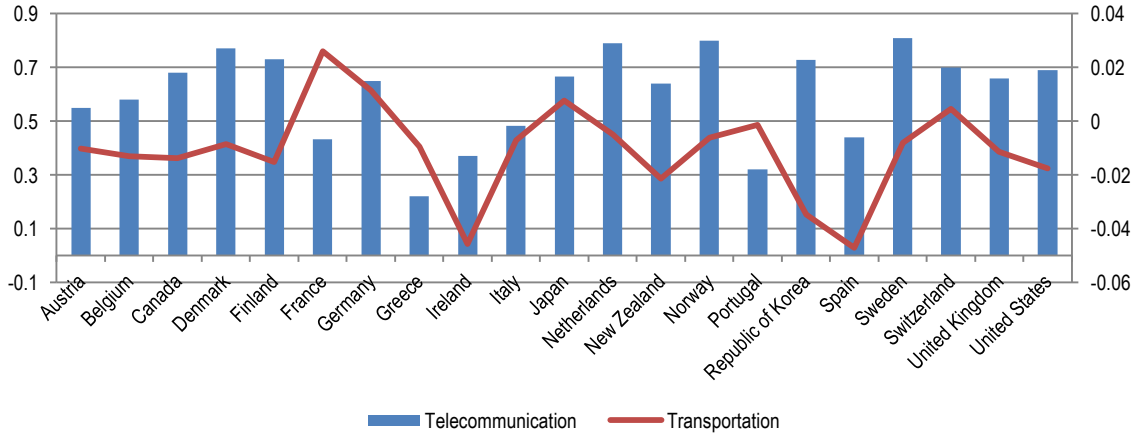


Fig. 2 Growth of broadband penetration rate and motorway capital



(a) year 2000



(b) year 2005

Note: Transportation infrastructure is indicated in the right axis.

Fig. 3 Productivity contribution of motorway capital for two groups.

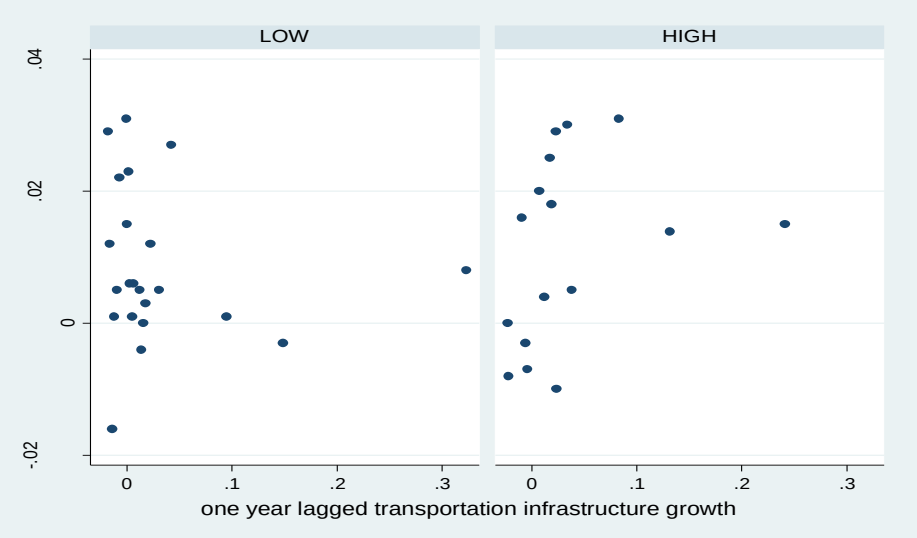
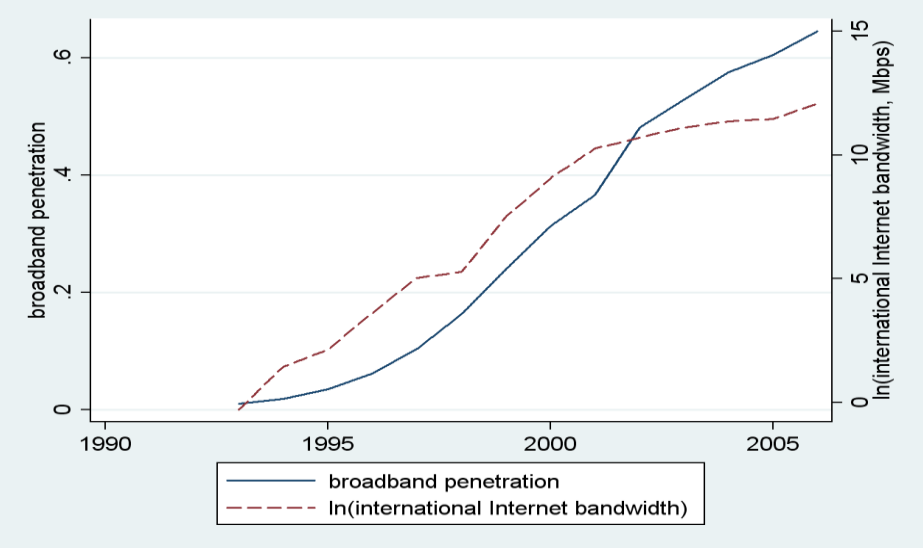
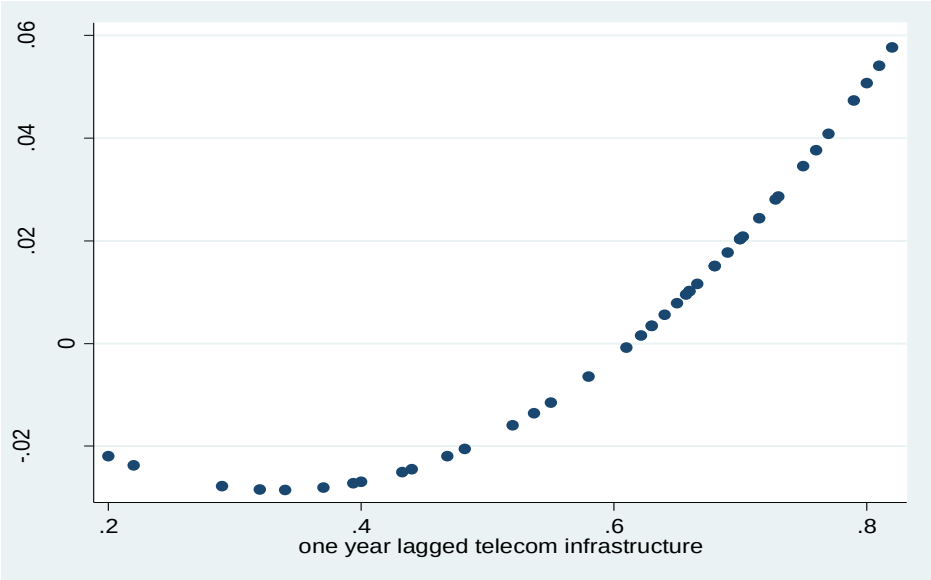


Fig. 4 Telecom infrastructure in OECD countries



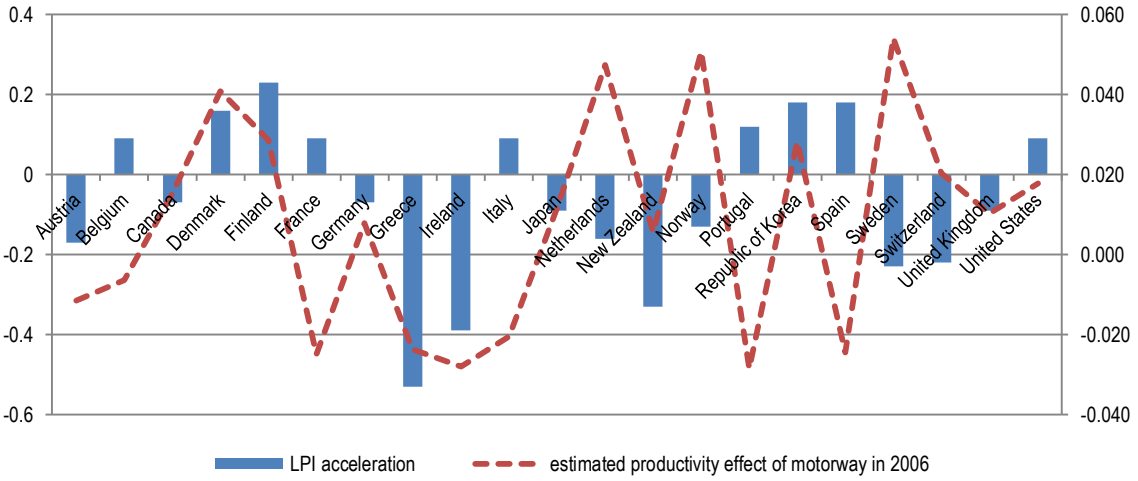
Note: International Internet bandwidth is indicated in the right axis.

Fig. 5 Productivity effect between telecom and transportation infrastructures



Note: The estimated productivity effects is given as $\frac{\Delta \ln \mathrm{TFP}_{it}}{\Delta \ln z_{it-1}} = \widehat{\gamma_0} + \widehat{\gamma_1} n_{it-1} + \widehat{\gamma_2} n_{it-1}^2$ for Model 4.

Fig. 6 Estimated productivity effect of motorway and LPI acceleration



Note: Estimated productivity effect is indicated in the right axis. Countries are listed in alphabetical order.

Appendix

A1 Logistics Performance Index

Table A1 LPI in OECD countries

Country	2007 ranking	2007 LPI	2010 ranking	2010 LPI	2012 ranking	2012 LPI	LPI acceleration (2007-2012)
Austria	5	4.06	19	3.76	11	3.89	-0.17
Belgium	12	3.89	9	3.94	7	3.98	0.09
Canada	10	3.92	14	3.87	14	3.85	-0.07
Denmark	13	3.86	16	3.85	6	4.02	0.16
Finland	15	3.82	12	3.89	3	4.05	0.23
France	18	3.76	17	3.84	12	3.85	0.09
Germany	3	4.10	1	4.11	4	4.03	-0.07
Greece	29	3.36	54	2.96	69	2.83	-0.53
Ireland	11	3.91	11	3.89	25	3.52	-0.39
Italy	22	3.58	22	3.64	24	3.67	0.09
Japan	6	4.02	7	3.97	8	3.93	-0.09
Netherlands	2	4.18	4	4.07	5	4.02	-0.16
New Zealand	19	3.75	21	3.65	31	3.42	-0.33
Norway	16	3.81	10	3.93	22	3.68	-0.13
Portugal	28	3.38	34	3.34	28	3.50	0.12
Republic of Korea	25	3.52	23	3.64	21	3.70	0.18
Spain	26	3.52	25	3.63	20	3.70	0.18
Sweden	4	4.08	3	4.08	13	3.85	-0.23
Switzerland	7	4.02	6	3.97	16	3.80	-0.22
United Kingdom	9	3.99	8	3.95	10	3.90	-0.09
United States	14	3.84	15	3.96	9	3.93	0.09

Source: World Bank (2007; 2010; 2012), Connecting To Compete: Trade Logistics in the Global Economy.

Note: Countries are listed in alphabetical order.

A2 Productivity growth

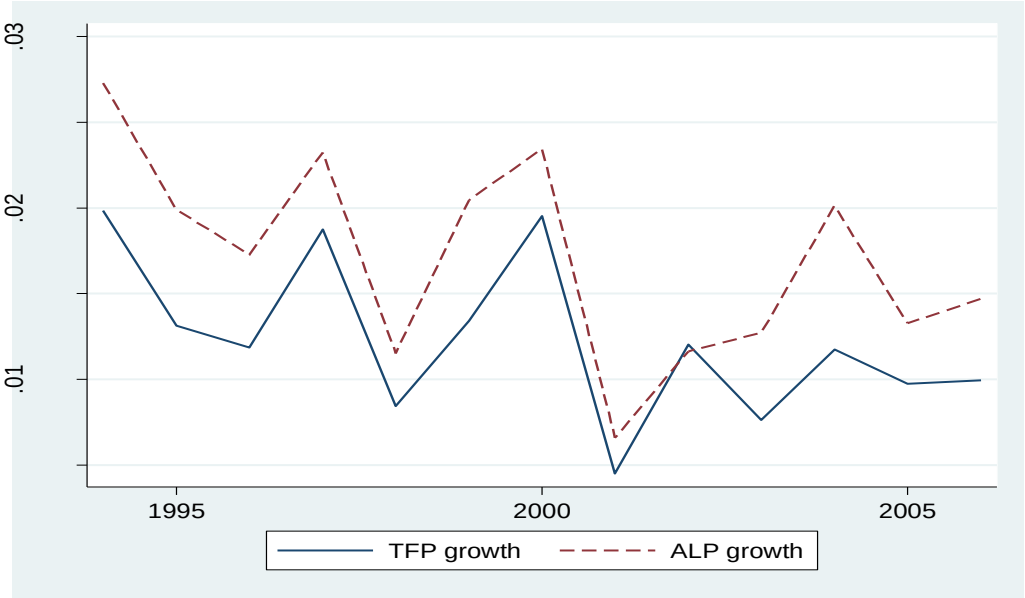


Fig. A1 Productivity growth in OECD countries

Source: OECD productivity database

A3 Estimation results for labor productivity growth

Table A2 Estimation results (ALP growth)

$\Delta lnALP_{it}$	Model i	Model ii	Model iii	Model iv	Model v	Model vi
	Fixed effect	Fixed effect	Diff. GMM	Fixed effect	Fixed effect	Diff. GMM
$\Delta lnALP_{it-1}$		0.209***	0.209***		0.169*	0.169**
		(0.062)	(0.057)		(0.089)	(0.080)
Δlnk_{it}	0.369***	0.365***	0.365***	0.305***	0.355***	0.355***
	(0.069)	(0.060)	(0.056)	(0.085)	(0.078)	(0.070)
Δlnz_{it-1}	0.011*	0.009**	0.009**	0.115*	0.113*	0.113**
	(0.006)	(0.004)	(0.004)	(0.060)	(0.056)	(0.050)
$ICT_{it-1}\Delta lnz_{it-1}$	-0.167**	-0.207***	-0.207***			
	(0.068)	(0.059)	(0.054)			
$ICT_{it-1}^2\Delta lnz_{it-1}$	0.243**	0.297***	0.297***			
	(0.104)	(0.085)	(0.079)			
$lnnb_{it-1}\Delta lnz_{it-1}$				-0.034*	-0.034*	-0.034**
				(0.019)	(0.017)	(0.015)
$lnnb_{it-1}^2\Delta lnz_{it-1}$				0.002*	0.002*	0.002**
				(0.001)	(0.001)	(0.001)
ΔS_{it}	0.033	0.027	0.027	0.173**	0.166**	0.166***
	(0.030)	(0.025)	(0.023)	(0.068)	(0.071)	(0.064)
$Open_{it}$	0.041**	0.028	0.028*	0.074**	0.058*	0.058**
	(0.017)	(0.018)	(0.016)	(0.033)	(0.029)	(0.026)
ΔlnV_{it}	0.009	0.004	0.004	-0.033	-0.052	-0.052*
	(0.029)	(0.028)	(0.026)	(0.031)	(0.034)	(0.030)
lnz_{it-1}	-0.000	-0.001	-0.001	-0.004	-0.002	-0.002
	(0.005)	(0.004)	(0.004)	(0.011)	(0.011)	(0.010)
Constant	-0.014	-0.017	-0.017	-0.073	-0.050	-0.034
	(0.040)	(0.033)	(0.030)	(0.083)	(0.087)	(0.076)
AR(1) p-value			0.0010			0.0050
AR(2) p-value			0.5901			0.7382
Sargan p-value			0.2173			0.2270
R^2	0.458	0.491		0.490	0.508	
Obs.	257	257	238	143	143	124

*, **, ***: Significant at the 10 percent, 5 percent, and 1 percent levels, respectively.

Note 1: The robust standard errors for panel data are reported in parentheses.

Note 2: Time dummies are included, but their results are not reported.

Note 3: In Difference GMM, every explanatory variable is treated as a predetermined variable except ΔlnV_{it} as endogenous variable. Arellano and Bond's (1991) specification test in Difference GMM rejects AR(1) but accepts AR(2). According to the Sargan test, Models iii, and vi satisfy the conditions for estimation of dynamic panel data.