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## Efficiency of transport infrastructure and ICT development

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# Efficiency of Transport Infrastructure and ICT Development

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## Abstract

This study examines the impact of ICT growth on the productivity effects of transportation infrastructure. Using dynamic panel data of OECD member countries, the study finds econometrically meaningful results on examining the complementarity between ICT and transportation infrastructures. The network effect of growth of motorway infrastructure in advanced 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

## **I. Introduction**

Transportation infrastructure enhances the quality and safety of mobility in the economy and promotes economic growth by increasing the returns to private investment and expanding the range of business opportunities. Investment in transportation infrastructure has been regarded as a key to economic development (World Bank, 2008). For developed countries, transportation accounts for 7 percent of GDP on average.

Among the various types of transportation infrastructure, road infrastructure has been examined the most often in empirical literature.<sup>1</sup> The motorway increases production efficiency by reducing the cost of physical distribution of products and raw materials, besides stimulating investment in the vehicle industry and passing on substantial spillover effects to the rest of the economy. Furthermore, the convergence of Information and Communication Technology (ICT) and transportation technology has led to the development of the so-called Intelligent Transportation System (ITS). As a result, the network effect of motorway infrastructure has been expanding over time.

According to UNECE (2012), ITS performance depends critically on the size and quality of ICT networks in the economy.<sup>2</sup> Empirical observations on recent data reveal that unless the broadband penetration ratio exceeds a certain threshold level, ITS efficiency improves very little. This study attempts to examine the effects of ICT development on the magnitude network effects of motorway growth. In particular, the study explores the possibility of accelerating the productivity effects that arise from widespread use of ICT in

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<sup>1</sup> See, for example, Sim and Yoon (2001); Choi, Kim, and Kim (2007); Kuniyama and Kaiyama (1998); Canning and Bennathan (2000); and Calderon and Serven (2003).

<sup>2</sup> Intelligent Transport System is explained in the next section. UNECE (2012) emphasizes that the capacity of ITS to offer a variety of services does not depend linearly with the size of information network. Only after the network reaches a certain threshold level, the system performs the expected roles properly.

transportation.<sup>3</sup>

The productivity effects of motorway infrastructure among OECD countries are investigated by Na, Hahn, and Yoon (2013). They show that the contribution of motorways to productivity growth in the economy tends to increase as the motorway extends over time. In other words, an accelerating network effect prevails when the motorway grows beyond the threshold level. They, however, do not investigate the source of these network effects. Using OECD panel data, this study complements the previous study by partially answering why the network effects of motorway infrastructure tend to accelerate when ICT infrastructure grows concomitantly beyond a certain threshold level.

## II. Information and Communication Technology and Intelligent Transport Systems

The purpose of ITS is to increase the efficiency and safety of transportation by applying ICT to transportation infrastructure. ITS consists of four subsystems, travelers, vehicles, traffic centers, and roadsides, all of which are connected through wide-area wireless communications, wire-line communications, vehicle-to-vehicle (V2V) communications, and dedicated short-range communications (DSRC).<sup>4</sup>

The services provided by ITS include Advanced Traffic Management Systems (ATMS), Advanced Traveler Information Systems (ATIS), Advanced Public Transportation Information Systems (APTIS), Commercial Vehicle Operations (CVO), and Advanced Vehicle and Highway Systems (AVHS).<sup>5</sup> In order to offer these services, ITS uses the sensor

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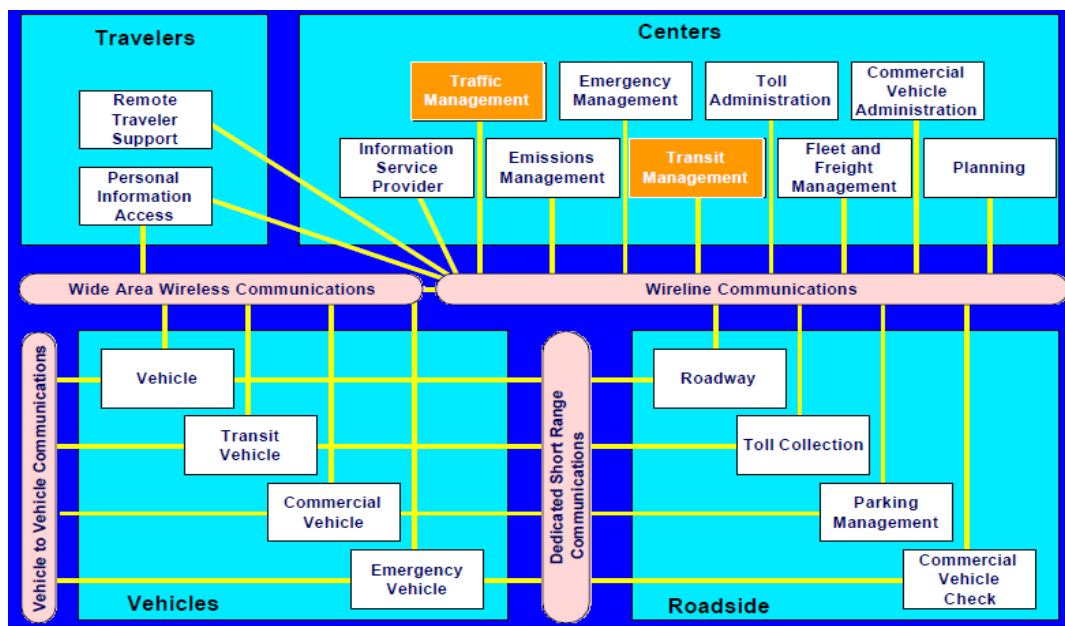
<sup>3</sup> The non-linear network effects of telecommunication infrastructure are examined in Röller and Waverman (2001) for OECD countries. Jung, Na, and Yoon (2013) examine the network effects of ICT infrastructure in Korea.

<sup>4</sup> An example of DSRC application is electronic toll collection (ETC).

<sup>5</sup> See Bonsall (2008).

technology, satellite GPS, wireless communication technology, and database management of transport information centers. In the recent past, wireless communication technologies that facilitate processing and the provision of user information on real-time basis have become essential, as an increasing number of drivers have been using smart phones.

Figure 1 Structure of Intelligent Transport System



Source: US Department of Transportation (2004).

Figure 1 illustrates the structure of an ITS by which traffic can be managed on real-time basis. ITS collects data from roads and running vehicles, controls the traffic flow by using roadside equipment for fast and safe movement, and provides travelers with traffic information. Normally, information on traffic volume, speed, and occupancy is collected through on-road vehicle detectors or CCTV, the collected information is processed in a traffic information center to make it fit for operators and users, and the information is then provided through Variable Message Sign (VMS), the Internet, or mobile phones. With the use of such real-time information, road users can choose the best route to their destinations. The biggest

advantage of real-time traffic information is that it helps disperse traffic volume and, therefore, reduce traffic congestion. As drivers obtain traffic information and change routes, high traffic volume on roads is dispersed into alternative routes, alleviating traffic congestion and improving the efficiency of traffic flows.<sup>6</sup>

In addition, ITS offers services related to the vehicle industry through communication networks. Drivers and passengers are offered mobile offices that handle traffic information, remote diagnosis of vehicles, and Internet services such as financial transactions, news, and e-mail. Motorway infrastructure can offer networked services based on sensor technology and become an Automated Highway System (AHS). For this, a sophisticated communication infrastructure for DSRC or a Continuous Air interface Long and Medium ranges (CALM) standard is needed.<sup>7</sup>

Most developed countries have targeted ITS as a national development strategy. The United States passed the Intermodal Surface Transportation Efficiency Act in 1991, and chalked out a plan to invest more than 20 billion US dollars until 2020. The European Union proposes an integrated ITS through a trans-European transport network.<sup>8</sup> According to the Presidential Council on National Competitiveness (2012) of the Republic of Korea, the global market for ITS is likely to grow by more than 10 percent per annum and reach 18.6 billion US dollars in 2015.

Table 1 Global market for ITS

(Unit: million US dollars)

|          | 2011     | 2012     | 2013     | 2014     | 2015     | CAGR (%) |
|----------|----------|----------|----------|----------|----------|----------|
| The U.S. | 5,089.62 | 5,884.94 | 6,049.92 | 6,577.11 | 7,141.32 | 9.57     |
| Canada   | 221.23   | 233.77   | 244.79   | 253.68   | 259.92   | 6.24     |

<sup>6</sup> See Korea Transport Institute (2012), p. 274.

<sup>7</sup> See Williams (2008) for wireless communication network technologies that are needed for ITS.

<sup>8</sup> Presidential Council on National Competitiveness (2012), Republic of Korea, Policy report.

|                 |           |           |           |           |          |       |
|-----------------|-----------|-----------|-----------|-----------|----------|-------|
| Japan           | 2,186.45  | 2,376.65  | 2,576.75  | 2,787.32  | 3,009.28 | 9.05  |
| The EU          | 4,082.45  | 4,448.31  | 4,830.01  | 5,233.80  | 5,665.38 | 9.45  |
| China           | 574.11    | 678.74    | 801.16    | 944.51    | 1,113.53 | 18.26 |
| Korea           | 294.26    | 326.49    | 361.74    | 400.12    | 441.63   | 11.47 |
| Other countries | 566.33    | 641.68    | 726.47    | 822.27    | 929.64   | 13.71 |
| Total           | 13,014.45 | 14,590.58 | 15,590.84 | 17,018.81 | 18,560.7 | 9.99  |

Source: The Presidential Council on National Competitiveness (2012).

### III. Empirical analysis

#### 1. Background

In most developed countries, investments in both ICT and motorway infrastructure have grown substantially during the recent decades. However, an exact comparison of the growth rates of the two different types of infrastructure is unfortunately difficult because the capital stock data on motorway infrastructure are not readily available. For expositional convenience, in this paper, we measure the motorway capital by motorway length per worker ( $z$ ). The motorway length and number of vehicles for the period 1996–2006 for 21 OECD countries are calculated from the OECD Factbook (2008).<sup>9</sup>

The data on GDP, total capital stock, and number of workers are obtained from the

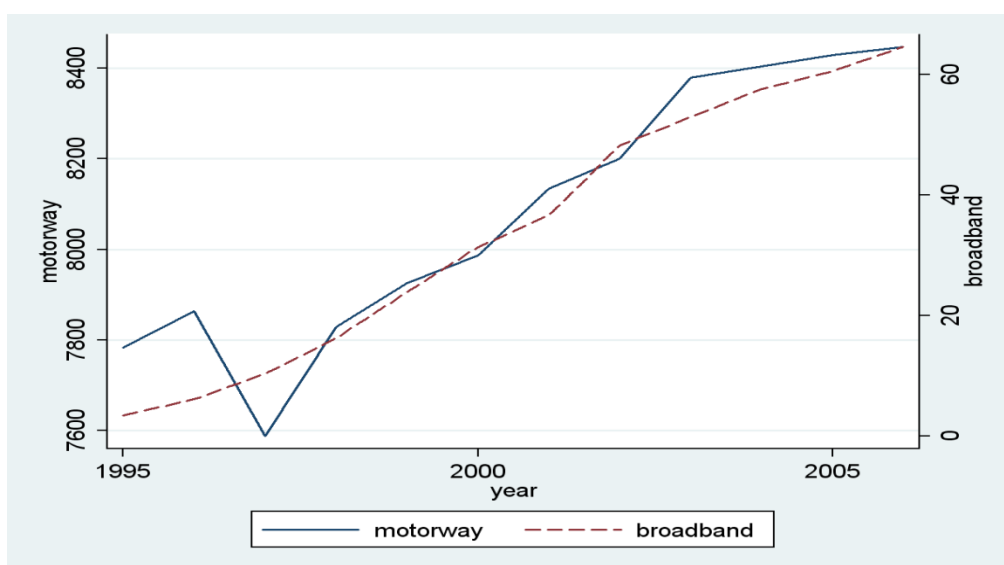
<sup>9</sup> This includes Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Japan, New Zealand, the Netherlands, Norway, Portugal, the Republic of Korea, Spain, Sweden, the Switzerland, the United Kingdom, and the United States.

According to OECD Factbook (2008), motorway is defined as follows: *Road, specially designed and built for motor traffic, which does not serve properties bordering on it, and which: (a) is provided, except at special points or temporarily, with separate carriageways for the two directions of traffic, separated from each other, either by a dividing strip not intended for traffic or exceptionally by other means; (b) does not cross at level with any road, railway or tramway track, or footpath; (c) is specially sign-posted as a motorway and is reserved for specific categories of road motor vehicles. Entry and exit lanes of motorways are included irrespectively of the location of the sign-posts. Urban motorways are also included.*

OECD Economic Outlook (2012) database, and each country's information infrastructure ( $ICT_{it-1}$ ) is measured by the number of broadband subscribers, as available in the ITU World Telecommunication-ICT Indicator (2010).

Figure 2 illustrates the investment trends in transportation and information infrastructure of OECD member countries. It is obvious that since the mid-1990s, both the ICT and motorway infrastructure began to grow together very rapidly until the early 2000s. While the ICT infrastructure continues to grow rapidly, the investment growth in motorway infrastructure shows a decline, reflecting fiscal austerity.

Figure 2 Time profile of investment in transportation and ICT infrastructure



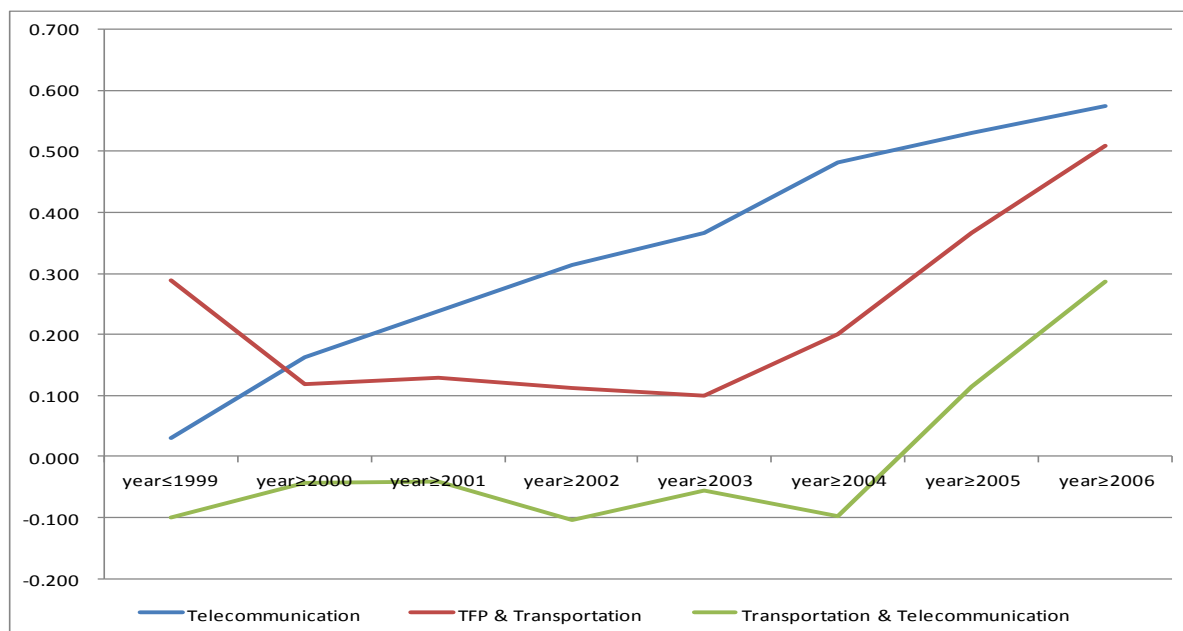
Source: OECD Factbook (2008) and ITU World Telecommunication-ICT Indicator (2010).

The efficiency contribution of each type of infrastructure is measured in terms of resulting change in total factor productivity (TFP), which can be obtained from the OECD productivity database. The control variables such as degree of openness of the economy and human capital, which affect the production efficiency of the economy, are obtained from the OECD Stat Extracts and Cohen and Soto (2007); these present the years of schooling for



persons 25 years and over.

Figure 3 Productivity relationship between telecom and transportation infrastructures



Note: Telecommunication denotes a lagged value of number of broadband subscribers ( $ICT_{it-1}$ ), while TFP and transportation denote a TFP growth rate of the current period ( $\Delta \ln TFP_{it}$ ) and the growth rate of motorway length per worker in the previous period ( $\Delta \ln z_{it-1}$ ), respectively.

Figure 3 shows that the telecom infrastructure of OECD countries, as measured by the broadband penetration ratio, has steadily increased since the late 1990s. The adjusted correlation coefficient (based on windowed cross-correlation technique) between the growth rates of transportation infrastructure (or motorway capital) and telecom infrastructure remained mostly negative prior to 2003, and began to increase rapidly after 2004, to remain positive. It is interesting to note that the correlation coefficient between the growth rates of TFP and the transportation infrastructure shows an inverted U-shape and began to increase only after 2003. In the next section, we empirically analyze the causality between these variables.

## 2. Model

We begin with the aggregate production function  $Y = AF(L, K)$ , where  $Y$  stands for the GDP,  $A$  represents the TFP, and  $L$  and  $K$  denote labor and capital stock, respectively. It is assumed that the TFP depends on the telecom and transportation infrastructure and is influenced by time- and country-specific socio-economic effects.

The basic model for our estimation is

$$\ln TFP_{it} = \alpha_{0i} + \alpha_i t + f(\ln z_{it-1}) + X_{it}\beta + \mu_t + u_{it},$$

where  $i$  and  $t$  represent the country and time period, respectively. In this model,  $\alpha_{0i}$  is the country-specific level of the TFP,  $\alpha_i t$  the country-specific trend coefficient, and  $z_{it-1}$  lagged road infrastructure;  $f(\cdot)$  denotes a non-linear functional relationship that describes the productivity impacts of motorway capital, while  $X_{it}$  denotes a vector of control variables, which include human capital, degree of congestion, and openness of the economy.<sup>10</sup> The error term  $u_{it}$  represents various macro variables, often containing unobservable factors, and is serially correlated. To control for country-specific trends and integrated errors, we propose a first-difference model as follows:

$$\Delta \ln TFP_{it} = \alpha_i + \Delta f(\ln z_{it-1}) + \Delta X_{it}\beta + \tau_t + \epsilon_{it}, \quad (1)$$

where  $\tau_t \equiv \Delta \mu_t$ ,  $\epsilon_{it} \equiv \Delta u_{it}$ .

We assume that  $\epsilon_{it}$  is independent over time. In other words, given the past

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<sup>10</sup> Fernald (1999) presented a theoretical model for the relation between capacity and use of roads. If motorway usage exceeds the given road infrastructure capacity, transportation cost increases from congestion. It is natural to use motorways as a control variable.

sequence of TFP growth rates, the current TFP growth rate depends on one-year lagged transportation and telecom infrastructure, global time effects, and unpredictable shocks. Finally, the following specification is used to estimate the effect of telecom infrastructure on the motorway infrastructure productivity effect:

$$\Delta \ln TFP_{it} = \alpha_i + (\gamma_0 + \gamma_1 D_{ICT>k}) \Delta \ln z_{it-1} + \Delta X_{it} \beta + \tau_t + \epsilon_{it}. \quad (2)$$

The dummy variable  $D_{ICT>k}$  takes the value of 1 when the telecom infrastructure or broadband penetration ratio exceeds  $k$ . Similarly, an alternative specification can be used to estimate non-linear network effects as follows:

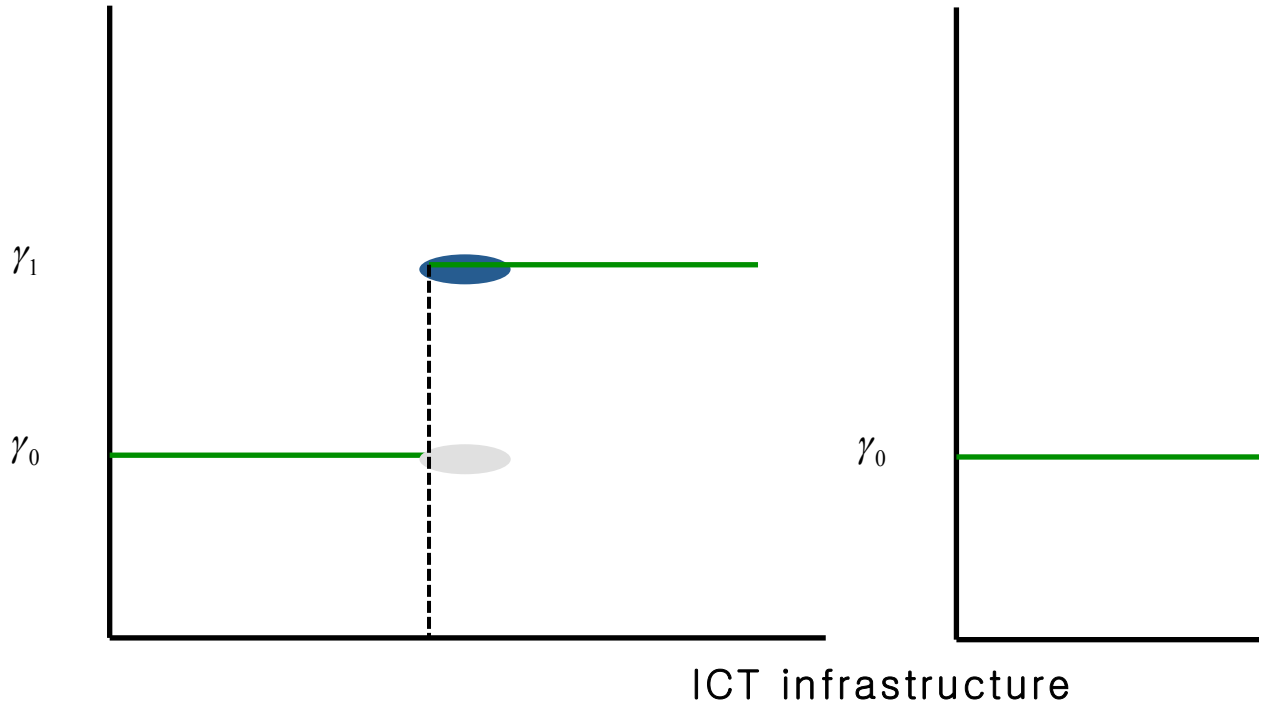
$$\Delta \ln TFP_{it} = \alpha_i + \{\gamma_0 + \gamma_1 \text{Max}(0, ICT_{it-1} - k)\} \Delta \ln z_{it-1} + \Delta X_{it} \beta + \tau_t + \epsilon_{it}. \quad (3)$$

The difference between the two specifications stems from the relationship between motorway capital and TFP growth. In place of the discontinuous jump in (2), continuity is preserved in (3). As the ICT infrastructure exceeds a certain threshold level, productivity growth increases linearly with motorway capital. Figure 4 compares the two different specifications.

Figure 4. Productivity impacts of motor way capital

## Effect of Transportation infrastructure

## ICT infrastructure



The robustness of the estimation results on the role of ICT and motorway infrastructure can be examined by estimating the effect of infrastructure on labor productivity growth. Given the constant returns to scale (CRS) production function,  $Y = AF(L, K)$ , we have  $\ln y_{it} = \ln A \{f(\ln z_{it-1})\} + \theta \ln k_{it}$ , where  $y_{it} = Y_{it}/L_{it}$ ,  $k_{it} = K_{it}/L_{it}$ , and  $\theta$  is the share of capital. Then, from Equation (3), the following equation can be obtained:<sup>11</sup>

$$\Delta \ln y_{it} = \alpha_i + \{\gamma_0 + \gamma_1 \text{Max}(0, \text{ICT}_{it-1} - k)\} \Delta \ln z_{it-1} + \Delta X_{it} \beta + \theta \Delta \ln k_{it} + \tau_t + \epsilon_{it}. \quad (4)$$

Equation (4) indicates that the effect of motorway capital on labor productivity

<sup>11</sup> 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).

growth depends in general on ICT infrastructure and a set of control variables,  $\Delta X_{it} = (\Delta S_{it}, Open_{it}, \Delta \ln V_{it})$ . The stock of human capital and degree of congestion are used as control variables for  $X_{it}$ . The data on average schooling are used for human capital ( $S_{it}$ )<sup>12</sup>, and congestion is measured by the proxy variable  $V_{it}$ , which measures the number of vehicles. Degree of openness ( $Open_{it}$ ) is measured as the ratio of trade volume to GDP.<sup>13</sup> The descriptive statistics of major variables are given in Table 2.

Table 2 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 |
| $\Delta S_{it}$       | 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 |
| $ICT_{it-1}$          | 356  | 0.245 | 0.259     | 0.860 | 0.000  |
| $\Delta \ln y_{it}$   | 335  | 0.017 | 0.015     | 0.074 | -0.028 |
| $\Delta \ln k_{it}$   | 302  | 0.029 | 0.020     | 0.119 | -0.160 |

### 3. Empirical results

Table 3 presents the fixed-effect estimation results for Equation (2).<sup>14</sup> The threshold level  $k$  is adjusted to vary between 0.5 and 0.8. Only when  $k$  exceeds 0.7, the estimated

<sup>12</sup> For human capital, we consider the Mincerian form (see Mincer, 1974; Heckman and Klenow, 1997; and Bils and Klenow), which, in its simplest form, specifies the logarithm of human capital as a linear function of years of schooling.

<sup>13</sup> Following Harrison (1996), openness is specified to influence TFP growth, not the TFP level.

<sup>14</sup> The Hausman test reveals that the p-value is close to zero.

coefficient for the impact of ICT becomes positive. Statistical significance is obtained when  $k$  increases further to 0.8. This result confirms that the productivity impact of motorway capital depends non-linearly on ICT infrastructure. Models (f) and (g) use two dummy variables to confirm that the productivity effect of motorway capital is positive and statistically significant when  $k = 0.8$ , below which the estimated coefficient can be negative.

Table 3 Estimation results [Equation (2)]

| $\Delta \ln TFP_{it}$          | Model (a)          | Model (b)           | Model (c)           | Model (d)          | Model (e)          | Model (f)           | Model (g)          |
|--------------------------------|--------------------|---------------------|---------------------|--------------------|--------------------|---------------------|--------------------|
| $\Delta S_{it}$                | 0.096<br>(0.061)   | 0.096<br>(0.061)    | 0.096<br>(0.061)    | 0.097<br>(0.061)   | 0.091<br>(0.061)   | 0.090<br>(0.061)    | 0.092<br>(0.062)   |
| $Open_{it}$                    | 0.060**<br>(0.021) | 0.061***<br>(0.021) | 0.065***<br>(0.020) | 0.058**<br>(0.021) | 0.059**<br>(0.021) | 0.061***<br>(0.021) | 0.057**<br>(0.021) |
| $\Delta \ln V_{it}$            | 0.021<br>(0.034)   | 0.021<br>(0.033)    | 0.023<br>(0.033)    | 0.020<br>(0.034)   | 0.019<br>(0.034)   | 0.020<br>(0.033)    | 0.019<br>(0.034)   |
| $\Delta \ln z_{it-1}$          | 0.008*<br>(0.004)  | 0.009**<br>(0.004)  | 0.010**<br>(0.004)  | 0.007*<br>(0.004)  | 0.007*<br>(0.004)  | 0.008**<br>(0.004)  | 0.007*<br>(0.004)  |
| $D_{50} \Delta \ln z_{it-1}$   |                    | -0.008<br>(0.019)   |                     |                    |                    |                     |                    |
| $D_{60} \Delta \ln z_{it-1}$   |                    |                     | -0.031<br>(0.026)   |                    |                    |                     |                    |
| $D_{70} \Delta \ln z_{it-1}$   |                    |                     |                     | 0.027<br>(0.027)   |                    |                     |                    |
| $D_{80} \Delta \ln z_{it-1}$   |                    |                     |                     |                    | 0.104*<br>(0.051)  | 0.101*<br>(0.050)   | 0.105*<br>(0.050)  |
| $D_{5080} \Delta \ln z_{it-1}$ |                    |                     |                     |                    |                    | -0.011<br>(0.020)   |                    |
| $D_{7080} \Delta \ln z_{it-1}$ |                    |                     |                     |                    |                    |                     | 0.021<br>(0.030)   |
| Constant                       | -0.015<br>(0.010)  | -0.016<br>(0.010)   | -0.017<br>(0.010)   | -0.015<br>(0.010)  | -0.014<br>(0.010)  | -0.015<br>(0.010)   | -0.014<br>(0.010)  |
| $R^2$                          | 0.222              | 0.222               | 0.227               | 0.223              | 0.223              | 0.224               | 0.224              |
| Obs.                           | 251                | 251                 | 251                 | 251                | 251                | 251                 | 251                |

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

Note 1:  $D_{50}$  and  $D_{5080}$  denote the dummy variables for  $ICT_{it-1} > 0.5$  and  $0.5 < ICT_{it-1} \leq 0.8$  respectively.

Note 2: The robust standard errors for panel data are reported in parentheses.

Note 3: Time dummies are included, but their results are not reported.

The estimated coefficients for the control variables such as degree of openness turn out to be statistically significant, while the coefficients for the other control variables are not significant [see Na, Hahn, and Yoon (2013)]. Although Equation (2) shows that non-linear network effects are pervasive, this does not reflect the growth effect of motorway extension. We use Equation (2) to search for the threshold effects.

Table 4 presents the estimation results for Equations (3) and (4). Both the fixed-effect and dynamic panel data estimation results are summarized. The AR(1) process is adopted in dynamic panel data estimation.<sup>15</sup>

Since the broadband penetration ratio of OECD countries could reach 60 percent only after 2005,  $k$  is adjusted to 0.6.<sup>16</sup> We find that Model (1) is static, while Model (2) is dynamic. Model (3) adopts the difference GMM. In any model, the estimated coefficient ( $\gamma_1$ ) 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.

Table 4 Estimation results [Equations (3) and (4),  $k = 0.6$ ]

|  | $\Delta \ln TFP_{it}$ | $\Delta \ln y_{it}$ |
|--|-----------------------|---------------------|
|--|-----------------------|---------------------|

<sup>15</sup> See Arellano and Bond (1991) and Arellano and Bover (1995) for an analysis of efficient estimator for dynamic panel data in the presence of endogeneity.

<sup>16</sup> The cross-correlation results between motorway and ICT infrastructure turned positive in 2005 when the average broadband penetration of OECD countries reached 0.605. The exogenous level for  $k$  is determined taking into account these data.

|  | Model (1)           | Model (2)          | Model (3)           | Model (4)           | Model (5)           | Model (6)           |
|--|---------------------|--------------------|---------------------|---------------------|---------------------|---------------------|
|  | FE(static)          | FE(dynamic)        | Diff GMM            | FE(static)          | FE(dynamic)         | Diff GMM            |
| $\Delta \ln TFP_{it-1}$                                    |                     | 0.050<br>(0.069)   | 0.050<br>(0.064)    |                     |                     |                     |
| $\Delta S_{it}$  | 0.095<br>(0.060)    | 0.091<br>(0.058)   | 0.091*<br>(0.055)   | 0.033<br>(0.031)    | 0.028<br>(0.027)    | 0.028<br>(0.025)    |
| $Open_{it}$  | 0.056**<br>(0.021)  | 0.054**<br>(0.022) | 0.054***<br>(0.020) | 0.034*<br>(0.016)   | 0.022<br>(0.017)    | 0.022<br>(0.016)    |
| $\Delta \ln V_{it}$  | 0.019<br>(0.034)    | 0.018<br>(0.034)   | 0.018<br>(0.032)    | 0.012<br>(0.031)    | 0.008<br>(0.030)    | 0.008<br>(0.028)    |
| $\Delta \ln z_{it-1}$                                      | 0.006<br>(0.004)    | 0.006<br>(0.004)   | 0.006*<br>(0.004)   | 0.005<br>(0.003)    | 0.003<br>(0.004)    | 0.003<br>(0.004)    |
| $\text{Max}(0, ICT_{it-1} - k) \times \Delta \ln z_{it-1}$ | 0.401***<br>(0.130) | 0.384**<br>(0.134) | 0.384***<br>(0.125) | 0.314*<br>(0.152)   | 0.267*<br>(0.130)   | 0.267**<br>(0.121)  |
| $\Delta \ln y_{it-1}$                                      |                     |                    |                     |                     | 0.190***<br>(0.063) | 0.190***<br>(0.059) |
| $\Delta \ln k_{it}$  |                     |                    |                     | 0.357***<br>(0.065) | 0.352***<br>(0.059) | 0.352***<br>(0.055) |
| Constant   | -0.014<br>(0.010)   | -0.014<br>(0.010)  | -0.014<br>(0.009)   | -0.010<br>(0.007)   | -0.009<br>(0.007)   | -0.004<br>(0.006)   |
| $R^2$  | 0.226               | 0.228              |                     | 0.453               | 0.481               |                     |
| Obs.   | 251                 | 250                | 231                 | 257                 | 257                 | 238                 |

\*, \*\*, \*\*\*: 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  $\Delta \ln V_{it}$ .

Note 4: Arellano and Bond's (1991) specification test in Difference GMM rejects AR(1) but accepts AR(2).

According to the Sargent test, Models (3) and (6) satisfy the conditions for estimation of dynamic panel data.

In Model (3), when  $k$  is less than 0.6, the effect of growth of motorway capital on TFP growth is only 0.006. On the other hand when  $k$  exceeds 0.6, ICT infrastructure complements motorway capital and produces a statistically significant additional beneficial effect of  $\{0.384(\gamma_1) \times (ICT_{it-1} - 0.6)\}$ . 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  $0.006(\gamma_0) + 0.0384(\gamma_1 \times 0.1) = 0.039$ . In other words, when

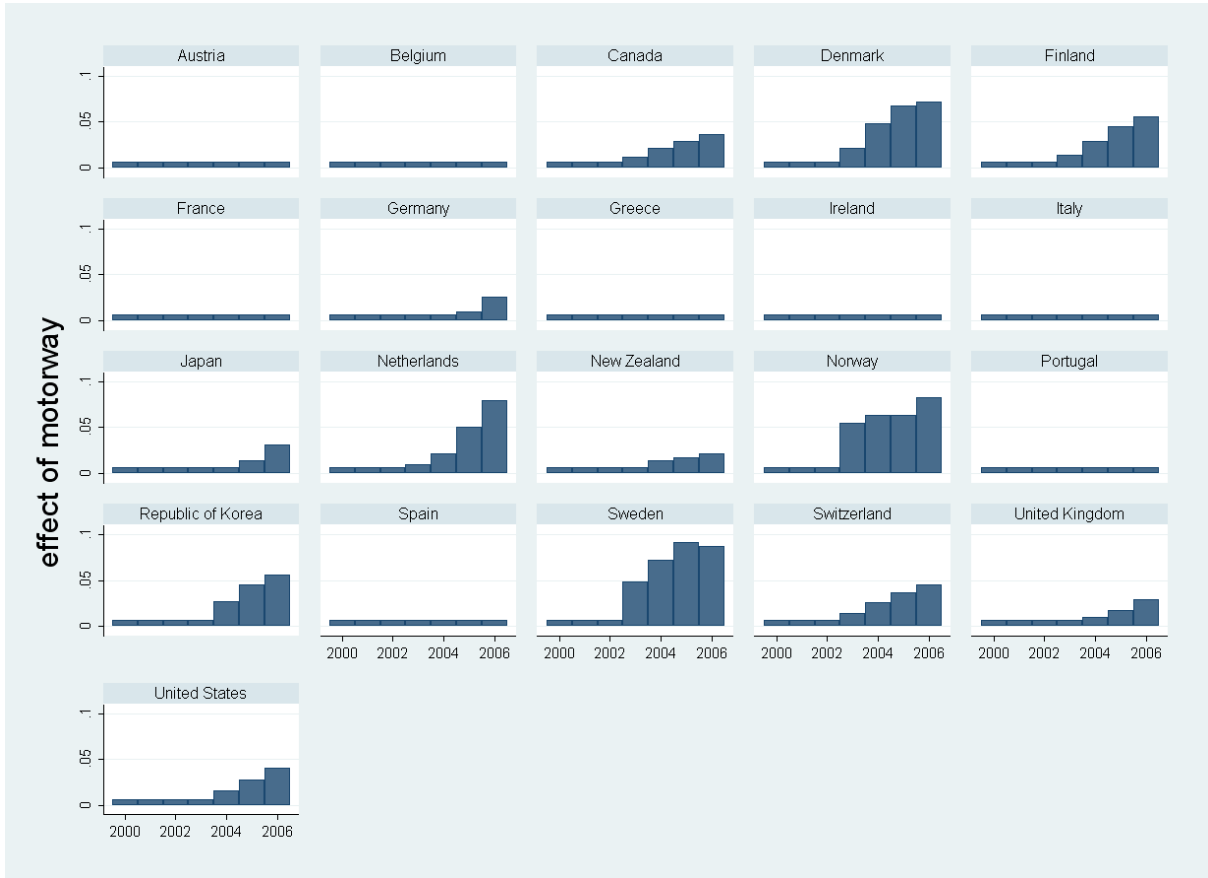


the ICT infrastructure exceeds a certain threshold level, it complements motorway capital in TFP growth. Figure 5 reports the productivity effect of motorway capital for individual OECD member countries at each time point.

Models (4) to (6) present the estimation results for Equation (4). Again, we see that a complementarity between ICT and motorway infrastructure prevails when the ICT infrastructure grows beyond a certain threshold level. In other words, the effect of motorway capital on labor productivity depends critically on the broadband penetration ratio of each country. The degree of openness of an economy seems to contribute to TFP growth as well. The estimated range for a share of capital is 0.352–0.357 and statistically significant.

Our estimation results confirm the necessary conditions for productivity impacts of ITS in UNECE (2012). The convergence of ICT and transportation technology engenders the accelerating network effects of motorway infrastructure only when the ICT infrastructure grows beyond a certain threshold level. It is interesting 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 60 percent in 13 countries, including the Republic of Korea, the United States, and Japan. As shown in Figure 5, the productivity effect of motorway infrastructure has been accelerating recently in these countries.

Figure 5 Productivity effects of motorway infrastructure among OECD countries [Model (3)]



Note: The effect of motorway  $\frac{\Delta \ln TFP_{it}}{\Delta \ln z_{it-1}}$  was calculated as  $\gamma_0 + \gamma_1 \times \text{Max}\{0, (ICT_{it-1} - k)\}$ .

#### IV. Concluding comments

The productivity effects of infrastructure investment need to be closely examined under fiscal austerity measures. This study presents a simplified analysis of complementarity 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 complementarity can be applied to the developing countries as well because ICT convergence takes place also in developing countries.

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