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Path dependence and the geography of infrastructure networks: the case of the European fibre-optic network

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Abstract We analyse the path dependent dynamics in the formation of new infrastructure using an augmented gravity model. We observe that the formation of the pan-European telecommunication backbone has been dependent on pre-existent European transportation networks, particularly, the maritime and railway networks. Cities that were already central in these transportation networks were more likely to get connected through fibre-optic networks than other cities. Our study can be considered as a first attempt to analyse, in a quantitative manner, the path dependent dynamics in the formation of new infrastructure.

Keywords Internet · Evolutionary theory · Gravity model

JEL Classification O30 · R10 · R11 · R12

1 Introduction

We present a study of the fibre-optic network among European cities, also often termed as the telecommunication backbone infrastructure (Rutherford et al. 2004). We start from a standard gravity model where connectivity levels between city-pairs are explained by the respective sizes of two cities and geographical proximity. We argue,

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however, that the exact geography of the fibre-optic network is to be understood in an historical context where pre-existing infrastructure network connections may affect the construction of new fibre-optic connections. That is, we expect the development of the fibre-optic network to have been path dependent on pre-existing urban networks of an infrastructural kind. We focus on those transportation infrastructures that rendered the construction of cable infrastructure less costly: railway and maritime networks. We show that, apart from the standard variables representing mass and distance, the fibre-optic network is indeed shaped by the pre-existing railway and maritime networks in the sense that cities hosting either a seaport or a major railway station are disproportionally better connected than other cities.

We will proceed as follows. In Sect. 2 we substantiate our claim that the geography of new infrastructures, like the recent construction of the fibre-optic network, is not only driven by city size and distance, but is also structured by the pre-existing geographies stemming from infrastructures inherited from the past. Following our discussion, we present our augmented gravity model in Sect. 3, including the empirical data we use to capture functional specialization and physical infrastructures. We discuss our estimation results in Sect. 4, and we end with some concluding remarks in Sect. 5.

2 Path dependence

Famously, Tobler (1970, p. 236) proposed that the first law of geography should be that: "Everything is related to everything else, but near things are more related than distant things". Essentially, this law builds on the idea that the strength of relationships is sensitive to geographical distance, with the cost of interaction increasing with distance. Closely related to Tobler's "first law" is the widespread use of the gravity equation in geography, which explains the strength of interaction between two places by their respective sizes and the geographical proximity between them.

The gravity model has been mainly applied to explain trade flows between countries, a tradition going back to Tinbergen (1962) and Poyhonen (1963). Another application has been the analysis of bilateral trade flows between regions, both within and across countries, to estimate the negative effect of national borders on trade, as pioneered by McCallum (1995). More recently, other spatial flows stemming from social interaction have been analysed using the gravity equation including patent citations (Peri 2005), scientific collaboration (Ponds et al. 2007), mobile telephone calls (Krings et al. 2009) and inter-firm relations (Van Oort et al. 2010).

We expect that the gravity equation will also explain quite well transportation infrastructure capacity between cities as transportation capacity follows closely inter-city demand for goods and services. For example, as is the object of our study, the capacity of fibre-optic cables connecting European cities is expected to be highest between large and proximate cities (Zook 2005). The geographical location of cities plays a role in the shape of the network since most cities will be only connected to the nearest cities. This logic of geographical proximity follows from the fact that infrastructure costs increase with geographical distance. Usage is a second important determinant, because the demand for bandwidth will determine the profitability of cables. The gravity equation, then, holds that the connectivity between two cities is a negative function of geographical distance between two cities and a positive function of the sizes of two cities, reflecting the mass variable in the gravity law.

An important limit of the standard gravity model, however, holds that it is a-historical in ignoring the pre-existence of other infrastructures that may affect the formation of new infrastructure. In particular, in places already well connected through existing infrastructure networks it may be significantly cheaper to construct new infrastructure, since infrastructures are often bundled. Hence, the better connected two cities already are in existing networks, the more likely they get connected in the future in the new infrastructure network, a case of path dependence (Arthur 1994). Given the infrastructures inherited from the past, path dependencies are likely to exist in that pre-existing infrastructure geographies, quite literally, ‘pave the way’ for new infrastructures.

Regarding the influence of pre-existing physical infrastructures on the fibre-optic network, we assume that those cities that already linked through maritime or railway infrastructure are more likely to become linked through fibre-optic cables as well. Indeed, past research showed that the geography of Internet infrastructure is affected by existing urban concentrations of knowledge and nodes of transport provision (Tranos 2013; Tranos and Gillespie 2009, 2011). One reason for such path dependence holds that the pre-existence of physical infrastructures making is less costly to lay down cables. This is especially apparent in the railway system where cables can be laid down alongside the train tracks. Similarly, it is less costly to install cable infrastructure through the sea than into the ground. What is more, the major connections between Europe and North America are provides by sea cables through the Atlantic Ocean connecting European port cities to Washington DC and New York, mostly (Townsend 2001). More generally, one can expect new infrastructures to reproduce existing geographical inequalities, as the socio-economic determinants of infrastructure provision, which includes local demand, educated workforce and good governance tend to be the same across infrastructures (Perkins and Neumayer 2011).

Below, we test this path dependence thesis that pre-existing physical infrastructures that were already connecting European cities are likely to have structured the development process of fibre-optic network. More specifically, we expect that cities hosting either a seaport or a major railway station will be better connected than other cities, *ceteris paribus*. Below, we develop an augmented gravity model in which the pre-existence of seaports and major railway stations are captured by dummies. Our contribution is to provide further econometric evidence to earlier claims about the path dependence in infrastructure development.

3 The model

Newton’s gravity model for spatial interaction between the two objects i and j is specified as follows:

$$I_{ij} = K\frac{M_i^{\alpha 1} \cdot M_i^{\alpha 2}}{d_{ij}^{\beta}} \tag{1}$$

with $\alpha_1 = \alpha_2 = 1$ and $\beta = 2$.

This equation can also be used as a general gravity model of spatial interaction between spatial units i and j, where the parameter values of α and β can be estimated by:

$$\ln(I_{ij}) = \ln(K) + \alpha \ln(M_i \cdot M_j) - \beta \ln d_{ij} \tag{2}$$

Note that we can estimate a single parameter α as the matrix of interactions is symmetric in our case of the fibre-optic network.

3.1 Data

In the pan-European telecommunications backbone network, cities are connected physically by fibre-optic cables, either directly or indirectly. The gravity model estimates the direct physical capacity between each two city pairs (which, in most cases is actually zero). However, in the absence of capacity data, we proxy capacity by the number of providers that are active on the specified connection.[1] Thus, the dependent variable *CONNECTIVITY* is the number of active providers between two cities. Here, we assume that the number of providers operating between two cities give an indication about the bandwidth provided between two cities (Rutherford et al. 2004). The data are based on 2001-data provided by http://www.telegeography.com, kindly provided by Rutherford et al. (2004).

Figure 1 shows the Internet infrastructure network in 2001 in Europe, covering the whole continent. The map contains only cities that have at least one provider serving to another European city. The thickness of the links between cities represents the number of providers active between two cities. The number of nodes in the network adds up to 209 cities. Having 209 cities means we have 0.5(209 × 208) city pairs, which adds up to 21,736 observations in our regression analysis below. Out of these 21,736 observations, only 509 have non-zero values. The non-zero values range from 1 to 14.[2]

The *MASS* variable in gravity models often refers to population size, since the attractiveness of a region is proportional to the number of people residing in the region with whom people from other regions can interact. In our case we can assume that population alone is not effective to explain the connectivity between regions. Internet infrastructure is very dependent on the level of economic development of a region (Malecki 2002). Since demand for Internet services is highly related to income, one would prefer to use city income as the mass variable. However, currently information on income is not available at the city level; therefore we will use data at NUTS3 regional level. In this context we consider that NUTS3 regions are a good proxy for city level analysis as NUTS3 regions, for most countries, coincide with large cities and their suburbs. What is more, the Internet backbone connections in a city will be used not only by those located within the city, but also those located in close vicinity of a city. Data are taken from the ESPON dataset[3] and refer to the year 2003. Every

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[1] Admittedly, capacity is an imprecise indication of usage, since the utilization rates may well differ regionally. On this, see Devriendt et al. (2010).

[2] For a map for the US, see Liu et al. (2012).

[3] European Spatial Planning Observation Network, http://www.espon.net.

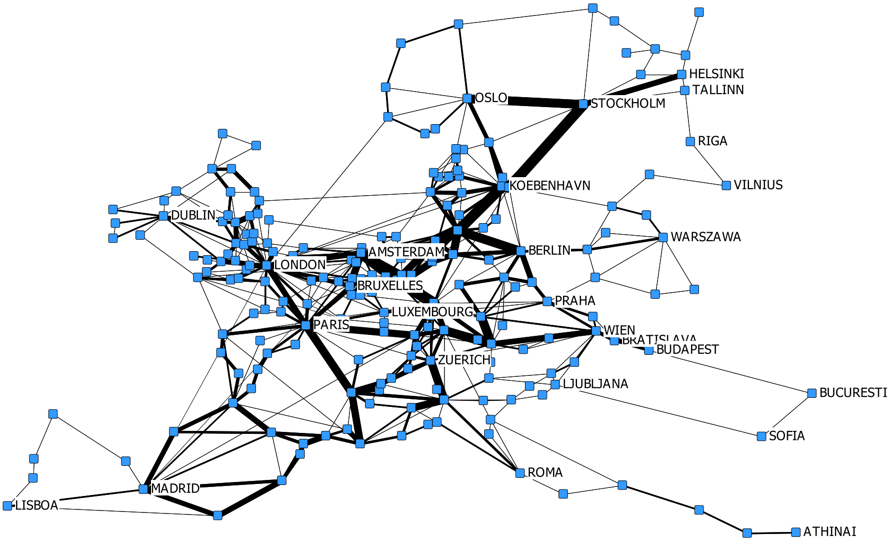

Fig. 1 Graph representing the internet infrastructure network in 2001. The thickness of the lines (from 1 to 14) is directly proportional to the number of providers serving that connection

city was allocated to a NUTS3 region. In case more than one city is present in a region, the value of GRP was equally divided by the number of cities located in the region. The *MASS* variable is then obtained by taking the product of regional population and GRP per capita for each NUTS3 region.

The *DISTANCE* variable is measured as geographical distance between each pair of cities is calculated by physical distance (as the crow flies) expressed in kilometres based on the geographical coordinates of the cities.

The variable *SEAPORT* indicates whether both cities are seaport cities. We defined seaport cities those cities located at the sea cost, or less than 15 km away from the seacoast. In addition, we included seaport of the cities of Amsterdam, Bordeaux and Hamburg which are cities with major ports located more than 15 km from sea.

The second infrastructure variable we constructed concerns the variable *TRAIN-STATION*. Here, we indicate city pairs where both cities are train hubs. Hubs were defined as train stations from which at least five different tracks to other cities ("a node with at least degree 5"). The tracks were observed from the maps provided by Thorsten Büker.[4]

The variable *SAMECOUNTRY* indicates whether or not both cities belong to the same European country. We introduced this variable as we expect that Internet providers offer connections mainly within the same country rather than crossing borders. It is often the case that national regulations are applied during the construction of infrastructure (e.g. land use regulations) and only in a few cases borders are crossed in order to guarantee international communication. What is more, most Internet communication is domestic, which means that the demand for bandwidth between cities at

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[4] Railways through Europe, http://www.bueker.net/trainspotting/maps.php.

two sides of a border will be less than two at the same distance within country borders (cf. McCallum 1995). Thus, this variable captures the effect of national regulations and, at the same time, the effect of domestic demand.

As a second control variable, we also include a dummy *AIRPORT*, which indicates city pairs that both have an airport operating in 2004 (extracted from EUROSTAT website[5].). Unlike seaports and train stations, the physical infrastructure provided by airports in itself will not render the construction of fibre-optic cables less costly. Rather, the presence of airports can be considered a proxy for the presence of sectors that require high-quality telecommunication infrastructure for their operations. Businesses co-locating with airports, including multinational companies and logistic services, are generally globally operating business that will also exert significant demand for Internet services (Castells 1996; Malecki 2002).

The variable *CAPITAL* indicates whether there is at least one capital city in the considered city pair. We assume that capital cities are well-connected in the fibre-optic Internet network, since capital cities typically host administrative centres and government agencies; these organisations are intensive users of Internet connections for organizational and executive purposes. Since centres and agencies operate mostly on a national basis, or internationally with other capital cities, we constructed the dummy variable as referring to any relation that involves at least one capital city.

3.2 Model specification

Network data are usually represented by a so-called adjacency matrix, where 0 indicates that there are no links between that pair of nodes and 1 (or a different number) indicates presence of links (strength of links) between those two nodes. In our case, the matrix values refer to the number of providers active between two cities. Since we thus deal with count data, the use of alternative regression techniques is appropriate (Burger et al. 2009). The most common regression model applied to count data is the Poisson regression, in which the observed interaction intensity between two cities has a Poisson distribution with a conditional mean that is a function of the independent variables. However, the distribution of our dependent variable does not satisfy this criterion due to overdispersion and an excessive number of zeros. This is why we will make use of the zero-inflated negative binomial model (ZINB). The ZINB model assumes the existence of two latent variables, namely the *Always-0* group and the *Not-Always-0* group. Observations belonging to the *Always-0* group have an outcome of zero with a probability equal to 1, while those belonging to the *Not-Always-0* group, there is a nonzero probability to get a positive value (Long 1997). We use our independent variables to assess the latter observations only, why the traditional gravity model is estimated for the zero-inflated part of the regression.

In order to see whether the ZINB model is indeed appropriate we can make use of two tests: the Vuong statistic test (Vuong 1989) which compares ZINB with standard Negative Binomial Regression (NEGBIN) and the Likelihood-ratio test of $\alpha = 0$,

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[5] Official Eurostat database, http://epp.eurostat.ec.europa.eu/portal/page/portal/transport/data/database.

which compares ZINB with Zero-Inflated Poisson model. In Table 3, these tests indeed confirm that ZINB is the best specification we could use with our data.

4 Results

4.1 Descriptive statistics

Table 1 provides the descriptive statistics for the dependent and independent variables used in the regression analysis below. Recall again that the unit of analysis in the regression will not be the city, but the city pair. Table 2 provides the correlation matrix. One can readily understand the negative correlation between distance and same country (−0.5254) as two cities located in the same counties are generally located much closer than two cities located in different countries. Most other independent variables show

Table 1 Descriptive statistics for independent variables included in the analysis

Variables	Observations	*Mean*	Standard deviation	Min	Max
MASS	21,736	46.7284	1.2863	42.2895	53.0257
DISTANCE	21,736	6.7284	0.6836	2.9897	8.2005
SAMECOUNTRY	21,736	0.0875		0	1
CAPITAL	21,736	0.2422		0	1
SEAPORT	21,736	0.2011		0	1
TRAINSTATION	21,736	0.1311		0	1
AIRPORT	21,736	0.3623		0	1

Table 2 Correlation matrix for independent variables included in the analysis

	1	2	3	4	5	6	7	8
1. *CONNECTIVITY*	1.0000							
2. *MASS*	0.1166	1.0000						
	0.0000							
3. *DISTANCE*	−0.3000	−0.0744	1.0000					
	0.0000	0.0000						
4. *SAMECOUNTRY*	0.2432	0.0292	−0.5254	1.0000				
	0.0000	0.0000	0.0000					
5. *CAPITAL*	0.0410	0.3420	0.1652	−0.1059	1.0000			
	0.0000	0.0000	0.0000	0.0000				
6. *SEAPORT*	0.0294	−0.0518	0.0630	0.0043	−0.0243	1.0000		
	0.0000	0.0000	0.0000	0.5288	0.0003			
7. *TRAINSTATION*	0.0999	0.2776	−0.1543	0.0562	0.1427	−0.1640	1.0000	
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000		
8. *AIRPORT*	0.0584	0.4179	0.1178	−0.0326	0.2273	0.0734	0.1130	1.0000
	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	

Table 3 Gravity model results with *CONNECTIVITY* as dependent variable

	Model 1	Model 2	Model 3	Model 4
Negbin part				
MASS	0.358** (0.036)	0.404** (0.038)	0.316** (0.038)	0.250** (0.042)
DISTANCE	−0.568** (0.086)	−0.688** (0.095)	−0.561** (0.085)	−0.915** (0.113)
SEAPORT		0.583** (0.110)		0.792** (0.117)
TRAINSTATION			0.326** (0.102)	0.535** (0.109)
AIRPORT				0.845** (0.109)
SAMECOUNTRY				0.620** (0.104)
CAPITAL				0.464** (0.122)
CONSTANT	−13.791** (1.548)	−15.629** (1.633)	−11.930** (1.631)	−8.487** (1.894)
Zero-inflated part				
MASS	−0.670** (0.060)	−0.647** (0.062)	−0.674** (0.060)	−0.586** (0.069)
DISTANCE	3.491** (0.165)	3.476** (0.174)	3.495** (0.165)	3.425** (0.198)
CONSTANT	13.944** (2.619)	12.797** (2.711)	14.126**(2.617)	9.666** (3.039)
α	0.669	0.721	0.642	0.773
Observations	21,736	21,736	21,736	21,736
Non-zero observations	509	509	509	509
Log likelihood	−1,917.919	−1,902.724	−1,912.875	−1,838.011
LR test of $\alpha = 0$[a]	149.82**	157.57**	141.82**	151.85**
Vuong test[b]	7.01**	6.84**	7.03**	5.74**

Significance levels: * $p < 0.05$, ** $p < 0.01$. Standard errors in parentheses

[a] Indicates whether negative binomial regression provides a better fit than Poisson regression [b] Tests whether zero-inflated negative binomial is preferred to standard negative binomial

low but positive correlations. Interestingly, the negative correlation between seaports and train stations (−0.1640) reflects opposite geographical logics: seaports are by definition located at the coasts while the major train stations are often in the centre of a country.

4.2 Estimation results

The regression results are presented in Table 3. Model 1 represents the classic gravity model, without any additional dummy variable. As expected, mass (gross regional product) positively influences connectivity, while distance has a negative sign reflecting that a larger distance decreases the connectivity between two cities. Note that in the inflated part these variables behave in the opposite way, as these variables explain zero values. This means, for example, that the more distant two cities are, the higher is the probability that there will be no provider operating between the two cities.

The likelihood-ratio test confirms that the negative binomial regression gives a better interpretation than a Poisson, since it shows significant results. Moreover, the Vuong test confirms our intuition of using the inflated version to fit the model; the test value is high and significant, which means that the ZINB is preferred to the standard NEGBIN.

Model 2 adds the port dummy to the classical gravity equation, while model 3 adds the trainstation dummy. Both are highly significant and of the expected sign. Hence, we can conclude that the path dependence hypothesis—which stated that a pre-existing infrastructures structure the formation of a new infrastructure—holds true. Cities that were already connected through seaports and major train stations, tend to reproduce this high level of connectivity in the fibre-optic network.

The final model 4 includes both the port and trainstation dummies, as well as all control variables. In this model, the effects found for the port and trainstation in model 2 and 3 remain stable, with the value of the coefficients becoming even stronger. The control variables are also significant and have the expected sign. We observe that, as expected, airport cities tend to be better connected in the fibre-optic network. Cities located in the same country tend to be better connected indicating border effects. Finally, those city pairs with at least one capital city also tend to be better served.

A final interesting finding in model 4 holds that, compared to model 1 as well as to models 2–3, the coefficient of physical distance is gaining in importance. This shows that the dummy variables especially explain connectivity between cities that are relatively far apart. The remaining connectivity is primarily driven by physical proximity underlying the classic gravity equation.

5 Concluding remarks

This study can be considered a first attempt to analyse the path dependent dynamics in the formation of new infrastructure. We have observed that the formation of the pan-European telecommunications backbone network has been dependent on the pre-existent European transportation networks, particularly, the maritime and railway networks. Cities that were already central in these transportation networks were more likely to get connected through fibre-optic networks than other cities. These path dependent dynamics have been probed using an augmented gravity model, thus taking into account the classic explanatory variables of mass and distance as well.

The outcomes of our study may explain that major cities, once they have become a major node in one network, are often able to leverage this advantage and to become dominant in newly emerging networks as well. The tendency for new infrastructures to reproduce pre-existing geographical inequalities also sheds further light on the apparent stability of urban size distributions, at least in Europe (Hohenberg and Lees 1995; Batty 2006), Our result also points to a mechanism behind the observation that, when measured of long periods of time, larger cities tend to grow faster than smaller cities in a number of countries (Pumain and Moriconi Ebrard 1997). That is, larger cities being typically well-connected through particular infrastructures, see their connectivity reproduced in new infrastructures. Since infrastructures are generally not substitutive but complementary, larger cities would then grow faster than smaller cities *ceteris paribus*.

Following our reasoning, predictions of future demand for new infrastructures can be rather easily derived from pre-existing infrastructure use, even if the reproduction of existing infrastructures geographies into new infrastructure will never be perfect. In this respect, spatial planning policies at the national level can be well informed. At the same time, from the perspective of urban and regional planning, the notion of path dependence suggests that policymakers have little degree of freedom in influencing the evolution of infrastructural systems. With the emergence of a new infrastructure, any attempt to develop a new node with poor accessibility in pre-existing infrastructures and little local experience in governance, is risky. Possibly, new nodes can gain prominence when specific conditions apply, such as exceptional complementarities between local users and the new infrastructures services (for example, the presence of military, university, or multi-national companies).

Our study can be regarded as a first step in an evolutionary approach to infrastructure, as part of a wider evolutionary program in economic geography and regional science (Boschma and Frenken 2006; Martin and Sunley 2006). Even if our analysis has been essentially static, by introducing variables that reflect the geographical structures that are inherited from the past, the theoretical notion of path dependence could be made operational. Cities that were already well connected in pre-existing transportation networks tended to reproduce this advantage in the level of connectivity in the fibre-optic network they achieve over time. In this context, the notion of 'regional path dependence' introduced by Martin and Sunley (2006) applies well, but then at the city level: cities central in one infrastructure network tend to reproduce this centrality in a newly emerging network.

We finally would like to point to some of the limitations of our study, which lie primarily in the quality of the data. The dependent variable we use (the number of providers active between two cities) is only a proxy of the fibre-optic capacity that would characterise best the structure of the Internet backbone network. What is more, we have chosen to use dummies for our independent variables as to indicate whether a city plays a major role in particular pre-existing networks. Obviously, the thresholds applied to construct the dummy variables are to some extent arbitrary, and in future studies one may prefer to construct continuous variables instead. Finally, the data are from 2001. Hence, we cannot assess whether the basic network structure has changed more recently. Nevertheless, given the path dependencies in usage patterns, major changes are not to be expected. Having said this, we hope to see more studies looking into the emergence of new infrastructures, both historical and contemporary, as to probe the path dependent dynamics of urban systems and the networks that hold them together.

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References

Arthur, W.B.: Increasing Returns and Path Dependence in the Economy. University of Michigan Press, Ann Arbor (1994)

Batty, M.: Rank clocks. Nature **444**, 592–596 (2006)

Boschma, R.A., Frenken, K.: Why is economic geography not an evolutionary science? Evolutionary economic geography. J. Econ. Geogr. **6**(3), 273–302 (2006)

Burger, M.J., van Oort, F.G., Linders, G.J.M.: On the specification of the gravity model of trade: zeros, excess zeros and zero-inflated estimation. Spatial Econ. Anal. **4**(2), 167–190 (2009)

Castells, M.: The Rise of the Network Society. Blackwell, Oxford (1996)

Devriendt, L., Derudder, B., Witlox, F.: Conceptualizing digital and physical connectivity: the position of European cities in internet backbone and air traffic flows. Telecommun. Policy **34**, 417–429 (2010)

Hohenberg, P.M., Lees, L.H.: The Making of Urban Europe 1000–1950. Harvard University Press, Cambridge (1995)

Krings, G.M., Calabrese, F., Ratti, C., Blondel, V.D.: Urban gravity: a model for inter-city telecommunication flows. J. Stat. Mech. L07003 (2009)

Liu, X., Neal, Z., Derudder, B.: Featured graphic. City networks in the United States: a comparison of four models. Environ. Plan. A **44**, 255–256 (2012)

Long, J.S.: Regression models for categorical and limited dependent variables. In: Advanced Quantitative Techniques in the Social Sciences, Vol. 7. Sage, Thousand Oaks (1997)

Malecki, E.J.: The economic geography of the internet's infrastructure. Econ. Geogr. **78**, 399–424 (2002)

Martin, R., Sunley, P.: Path dependence and regional economic evolution. J. Econ. Geogr. **6**(4), 395–437 (2006)

McCallum, J.: National borders matter: Canadian–U.S. regional trade patterns. Am. Econ. Rev. **85**(3), 615–623 (1995)

Perkins, R., Neumayer, E.: Is the internet really new after all? The determinants of telecommunications diffusion in historical perspective. Prof. Geogr. **63**(1), 55–72 (2011)

Peri, G.: Determinants of knowledge flows and their effect on innovation. Rev. Econ. Stat. **87**(2), 308–322 (2005)

Ponds, R., van Oort, F.G., Frenken, K.: The geographical and institutional proximity of research collaboration. Pap. Reg. Sci. **86**, 423–443 (2007)

Poyhonen, P.: A tentative model for the volume of trade between countries. Weltwirtschaftliches Arch. **90**, 93–99 (1963)

Pumain, D., Moriconi-Ebrard, F.: City size distributions and metropolisation. Geojournal **43**(4), 307–314 (1997)

Rutherford, J., Gillespie, A., Richardson, R.: The territoriality of pan-European telecommunications backbone networks. J. Urban Technol. **11**(3), 1–34 (2004)

Tinbergen, J.: Shaping the World Economy: Suggestions for an International Economic Policy. The 20th Century Fund, New York (1962)

Tobler, W.: A computer movie simulating urban growth in the Detroit region. Econ. Geogr. **46**, 234–240 (1970)

Townsend, A.M.: Network cities and the global structure of the internet. Am. Behav. Sci. **44**(10), 1697–1714 (2001)

Tranos, E.: The Geography of the Internet: Cities, Regions and Internet Infrastructure in Europe. Edward Elgar, Cheltenham (2013)

Tranos, E., Gillespie, A.: The spatial distribution of internet backbone networks in Europe: a metropolitan knowledge economy perspective. Eur. Urban Reg. Stud. **16**(4), 423–437 (2009)

Tranos, E., Gillespie, A.: The urban geography of internet backbone networks in Europe: roles and relations. J. Urban Technol. **18**(1), 35–50 (2011)

Van Oort, F.G., Burger, M.J., Raspe, O.: On the economic foundations of the urban network paradigm. Spatial integration, functional integration and urban complementarities within the Dutch Randstad. Urban Stud. **47**(4), 725–748 (2010)

Vuong, Q.H.: Likelihood ratio tests for model selection and non-nested hypotheses. Econometrica **57**, 307–333 (1989)

Zook, M.A.: The Geography of the Internet Industry: Venture Capital, Dot-coms and Local Knowledge. Blackwell Publishers, Oxford (2005)