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The ripple effects of large-scale transport infrastructure investment

Damiaan Persyn[1] | Javier Barbero[2] | Jorge Díaz-Lanchas[3] | Patrizio Lecca[3] | Giovanni Mandras[4] | Simone Salotti[5]

[1]Thünen Institute of Rural Economics and University of Göttingen, Göttingen, Germany

[2]Department of Economics, Universidad Autónoma de Madrid, Madrid, Spain

[3]Comillas Pontifical University, Madrid, Spain

[4]Cassa Depositi e Prestiti, Roma, Italy

[5]European Commission, Joint Research Centre (JRC), Seville, Spain

Correspondence

Simone Salotti, European Commission, Joint Research Centre (JRC), Seville, Spain.
Email: simone.salotti@ec.europa.eu

Abstract

We analyze the general equilibrium effects of an asymmetric decrease in transport costs, combining a large-scale spatial dynamic general equilibrium model for 267 European NUTS-2 regions with a detailed transport model at the level of individual road segments. As a case study, we consider the impact of the road infrastructure investments in Central and Eastern Europe of the European Cohesion Policy. Our analysis suggests that the decrease in transportation costs benefits the targeted regions via substantial increases in gross domestic product (GDP) and welfare compared to the baseline, and a small increase in population. The geographic information embedded in the transport model leads to relatively large predicted benefits in peripheral countries such as Greece and Finland, which hardly receive funds, but whose trade links cross Central and Eastern Europe, generating profit from the investments there. The richer, Western European nontargeted regions also enjoy a higher GDP after the investment in the East, but these effects are smaller. Thus, the policy reduces interregional disparities. There are rippled patterns in the predicted policy spillovers. In nontargeted countries,

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regions trading more intensely with regions where the investment is taking place on average benefit more compared to other regions within the same country, but also compared to neighboring regions across an international border. We uncover that regions importing goods from Central and Eastern Europe enjoy the largest spillovers. These regions become more competitive and expand exports, to the detriment of other regions in the same country.

KEYWORDS
economic geography, spatial dynamic general equilibrium modeling, transport infrastructure

1 | INTRODUCTION

Countries dedicate significant resources to transport infrastructure construction and maintenance. Vast investment projects are grounded on the expected positive economic returns of transport infrastructure (see, among others, Berg et al., 2017; Crescenzi et al., 2016). It is therefore surprising that there is no consensus among economists on the size or the direction of the effects expected from such investments on development at the regional and country level. Puga (2002), for example, emphasizes that roads can be used in both directions, hinting that an unintended consequence of lower transport costs could be that manufacturing moves away from peripheral regions and relocates to the industrial core. A reduction in transport costs due to infrastructure investments may unintentionally affect the complex interdependent location choices of workers and firms. Many channels operate simultaneously and depend on regional characteristics, such as endowments or geographic location, and on specific properties of the economic activity under consideration, such as the existence of economies of scale or differences in trade elasticities.

Early economic models considering the economic effects of lower transport costs, both numerically and analytically, were mainly set up to explore and highlight specific economic mechanisms rather than allowing for an assessment of the impact of transport infrastructure investment (Krugman, 1991, 1993). More recent contributions span from empirical ex-post assessments of transport infrastructure investments (Duranton et al., 2014; Koster et al., 2021) to multiregion models that are more ambitious in scale and complexity (Allen & Arkolakis, 2022; Fajgelbaum & Schaal, 2020; Hayakawa et al., 2021; Redding & Turner, 2015). Most of these contributions employ advanced general equilibrium models, but not at the detailed level of territorial and sectoral disaggregation of the model we propose here.

In this paper, we contribute to this literature by combining a detailed transport model with a large-scale spatial dynamic general equilibrium model calibrated on a unique data set available for all 267 NUTS-2 regions of the European Union (EU) and the United Kingdom, which accounts for bilateral trade in final and intermediate goods pertaining to 10 economic sectors. Many of the model components are relevant to determine the location of economic activities, such as the mobility of both labor and capital, the existence of increasing returns to scale in the sectoral production functions, and the trade in intermediate inputs used for production.

Our transport model relies on estimating a generalized transport cost (GTC) measure (Persyn et al., 2022; Zofío et al., 2014) for the NUTS-2 regions of the EU, considering a variety of components of road transport costs such as fuel costs and wages. The transport costs are calculated as the minimum cost route for a truck to move across a digitized European road network containing more than four million road segments, considering road type and geography.

By soft-linking this detailed model for transport costs to a large-scale spatial general equilibrium model, we aim to obtain a realistic prediction of how transport infrastructure investment and decreasing transport costs affect economic outcomes such as gross domestic product (GDP) changes in the spatial distribution of production.

As a case study, we study the long-run impact of transport infrastructure of the €30 billion of road transport infrastructure investments implemented in the context of the 2014–2020 European Cohesion Policy (ECP), which mainly targeted the low-income regions of the EU.[1] The stated goal of this policy is to achieve economic and social cohesion by reducing disparities between EU regions, thus promoting a more balanced and sustainable territorial development. Our analysis verifies whether these large-scale road infrastructure investments contribute to this goal. Some key questions we want to answer in this paper are: (i) Do the lower transport costs lead to a shift of economic activity to the periphery, which is receiving the funds, or instead to the existing economic core? (ii) How large are the effects on key variables such as GDP and trade flows? (iii) What is the economic impact in the regions not targeted by the investments? Are spillovers positive or negative? What is the geography of these spillovers?

Our analysis suggests that the decreases in transportation costs generate substantial increases in the trade, GDP, and welfare of the regions targeted by the policy. The size of the increase in GDP we find is substantial, considering that we are abstracting from any demand-side effects of the investments and we solely concentrate on the structural supply-side impact. Finally, we highlight the existence of a spatial structure of spillover effects. We find economic benefits in all the regions of the EU, including those in which the ECP funds are not spent. We uncover the role played by distance, national borders, and trade flows in shaping the distribution of the spillovers. We find that—apart from the regions immediately bordering the targeted areas— spillovers are not monotonically decaying with distance, but rather exhibit ripples. On average, within each country, regions with stronger trade ties to Eastern Europe are benefitting more compared to other regions within the same country. We also find that regions with strong trade links with Central and Eastern Europe benefit relatively more from spillovers.

The remainder of the paper is organized as follows. Section 2 reviews the literature on the economic assessment of transport infrastructure. Section 3 briefly explains the main features of the modeling framework with a focus on transport costs. Section 4 illustrates the application of the transport model to the road transport infrastructure investments of the ECP and contains the results of the simulations carried out with the spatial general equilibrium model. Finally, Section 5 concludes.

2 | LITERATURE REVIEW

A large body of literature has studied how transport costs and investments in transport infrastructure affect the location of economic activity (see, e.g., Behrens et al., 2018; Holl, 2004; Ramcharan, 2009; Redding & Turner, 2015) and other economic outcomes. The main tools to estimate the effects of transport infrastructure investments include cost–benefit analyses (usually focusing on immediate outcomes of single projects, but with recent examples expanding the scope to wider economic benefits; see Roberts et al., 2020), econometric methods, and economic models.

The existing econometric evidence suggests that transport infrastructure may affect output and GDP (Álvarez et al., 2016; Banerjee et al., 2020), employment (Adler et al., 2020), productivity (Arbués et al., 2015; Konno et al., 2021), and trade flows (Donaldson, 2018; Duranton et al., 2014). The exact sign and magnitude of the impact, however, depend on a number of factors including the geographic areas and time periods covered by the studies,

[1]The transport infrastructure investments and their regional allocation come from official data of the European Commission's DG REGIO, and are available on the Cohesion Open Data Platform (https://cohesiondata.ec.europa.eu/). The 2014–2020 Cohesion funds are split into 123 categories of intervention (https://webgate.ec.europa.eu/esiflegislation/pages/viewpage.action?pageId=34441370), of which we select the seven categories that are directly related to road transport infrastructure investments (from 28 to 34).

the adopted estimation methods, and the type of infrastructure (with roads usually estimated to have larger effects than other means of transportation; see Melo et al., 2013).

Beyond impacting the region where the infrastructure is built, road transport infrastructure generates important spillover effects. Among the studies finding positive spillovers, Arbués et al. (2015) estimate the impact of transport infrastructures located in neighboring regions in Spain to be 50% of that of the local infrastructures. Jiang et al. (2017) and Qi et al. (2020) also estimate positive spillovers in neighbor regions. Ahlfeldt and Feddersen (2018), Banerjee et al. (2020), and Ozbay et al. (2007) find that spillovers decrease with distance, while according to Konno et al. (2021), the spillover effects are positive, but the direct ones are negative. The findings of Adler et al. (2020) and Álvarez et al. (2016) appear of importance for our present study, as these authors find that spillover effects are related to trade flows and value chains. Álvarez et al. (2016) find that territories with larger trade links with those in which the transport infrastructure investments take place benefit more in terms of spillover effects, something that we also find in our analysis.

There are studies finding negative spillovers of transport infrastructure. For instance, Boarnet (1998) argues that the effects of transport infrastructure policy are very localized and may generate negative output spillovers. A reason why we, in contrast, find positive spillovers may be that we consider output in the long run in per-capita terms, while allowing for production factor mobility (see also Banerjee et al., 2020). More in general, there is evidence suggesting that the construction of transport infrastructures may create winners and losers (Baum-Snow et al., 2020; Faber, 2014) in line with the theoretical arguments put forward by Baldwin and Wyplosz (2019). This is another result which is consistent with our findings, as not all neighbors and trade partners of the regions in which the infrastructure investments take place are affected in the same way.

Beyond econometric studies, the effect of transport infrastructure on economic outcomes such as GDP, welfare, and trade has been considered in economic models. In most of these studies, econometrics is used for model calibration, and the effect of infrastructure is obtained through simulation. We distinguish three separate strands of literature that have unfortunately not interacted much with each other.[2]

The first strand of literature originated in the field of transportation research. These models often consider projects at a local scale and, therefore, put less emphasis on general equilibrium effects, even though recent works highlight the importance of considering the wider benefits of transport infrastructure projects beyond conventional cost–benefit analysis (Laird & Venables, 2017; Welde & Tveter, 2022). In contrast to these contributions, our aim is to consider large-scale infrastructure projects in which these general equilibrium effects play a role through changes in wages and the return to capital, the relocation of capital and labor between regions, or changing spatial patterns of specialization, trade flows, and consumption.

A second strand utilizes new economic geography models à la Krugman (1993) to explain how the interaction of increasing returns to scale and transport costs shape Fujita et al. (1999), the spatial allocation of the economic activity. Some notable examples include the works by Ago et al. (2006), Barbero and Zofío (2016), Barbero et al. (2018), and Fujita et al. (1999). Except for the last one, these models are limited to a small number of regions and are not calibrated with real data nor used for counterfactual evaluation. More recently, the effects of transport infrastructure investment have been considered in large structural general equilibrium models (so-called quantitative spatial models) such as those of Allen and Arkolakis (2014, 2022), Fajgelbaum and Schaal (2020), or Hayakawa et al. (2021).

[2]An important reason for using a model-based approach rather than pure econometrics stems from the fact the policy we are analyzing is currently being deployed (the EU member states have time until 2023 to spend the 2014–2020 ECP funds), and its long-run effects will operate slowly through migration and capital relocation in the future. Therefore, there is no actual data yet on the full effects of the transport infrastructure investments of the policy. The effects we report compare the regional outcomes given the policy shock, to the regional outcomes in a baseline scenario without a shock (Lecca et al., 2014). We perform this comparison with simulated rather than real data, thus there are no confounding factors or endogeneity issues to control for. Identification is guaranteed in that any observed effect (resulting from the model simulations) must stem from the applied shock.

These quantitative spatial models often consider urban phenomena such as commuting or congestion, which are missing from our model, which rather focuses on effects operating through interregional trade in goods and factor mobility over large distances. Relative to this literature, our model contributes by considering a richer economic structure, with many sectors and trade in intermediate inputs, thus allowing for "traditional" effects such as increased regional sectoral specialization in response to a decrease in transport costs, in parallel with effects operating through economies of scale, product and labor market imperfections, and migration. In this respect, our work is close to that of Blouri and von Ehrlich (2020), who combine a structural model with regional data and an exogenous shock (the EU regional transfers, including those related to transport infrastructures). However, by analyzing transport separately from the general equilibrium model, our approach allows for a rich modeling of transport costs compared to the fully analytic spatial quantitative models.

The third strand of literature is the analysis of transport infrastructure investments through large-scale computable general equilibrium (CGE) models, which have traditionally emphasized disaggregation along multiple dimensions that are often lost in the models discussed before, such as distinguishing between multiple sectors of production, different types of capital and labor, and detailed production structures with intermediate inputs. Examples of this approach can be found in Bröcker et al. (2010) and Haddad et al. (2011) for the analysis of the TEN-T European road network, or Rokicki et al. (2021) for Poland. Our work shares the detailed sectoral decomposition of production and trade, which is typical for the CGE literature, but our modeling of transportation is more detailed.

Our contribution consists in combining insights from these three model-based approaches. On the one hand, we take advantage of a dedicated transport model using detailed information on road networks across the EU NUTS-2 regions to estimate a comprehensive measure of transport costs (Persyn et al., 2022; Zofío et al., 2020). On the other hand, we create a soft link between our transport model and a detailed large-scale spatial dynamic general equilibrium model. The resulting level of detail in the modeling of transport costs and of the macroeconomy allows us to obtain realistic estimates of the local impact while revealing interesting patterns in spillovers to other regions, depending on geography and trade flows. Soyres et al. (2020) use an approach similar to ours, combining a transport tool to estimate the reduction in transport costs resulting from the construction of transport infrastructure of the Belt and Road Initiative with a structural general equilibrium analysis of the world economy. Their findings point toward large effects in countries where the new transport infrastructure is built and high spillover effects in countries close to it. As in Soyres et al. (2020), we find localized effects in targeted regions, but our model finds comparatively smaller positive spillovers in regions farther from the targeted regions. It must be noted that the spillovers found by Soyres et al. (2020) for richer countries such as Germany, which we also consider, are also limited. An explanation for the larger spillovers in Soyres et al. (2020) may be the scale of the infrastructure works, which span three continents, and are estimated to reduce transport costs by up to 65% between some pairs of countries, compared to the relatively smaller nature of the infrastructure works we consider, where the largest estimated reduction in transport costs between two regions is about 14%.

Our model contains many features such as migration and capital mobility, unemployment, imperfect output markets, and considers 10 sectors while allowing for interregional trade in final and intermediate goods. We, therefore, do not attempt to estimate all the parameters governing these relationships, but rather mostly use well-established values from the existing literature. This is a conventional strategy when using large-scale multisector, multiregion models. The complexity related to the existence of a multitude of channels in our model leads us to use regression analysis on the simulated data to uncover the main mechanisms driving the results, and facilitate the interpretation of the outcomes of the model. This approach is different from quantitative spatial models focusing on a limited number of mechanisms and offering detailed estimations of the few key parameters behind them. An advantage of our approach is that we are forcibly open-minded about which mechanism drives the results. In our case, the analysis of the simulation results suggests that high unemployment may increase the local impact of transport investment and that backward linkages are particularly important in explaining spillovers. Results like this one would have been missed by a more targeted analysis, which would typically exclude trade in intermediate

goods. Further analyses, also purely econometric, would certainly constitute an interesting avenue of research, but would go beyond the scope of our paper.

3 | THE MODELING FRAMEWORK

3.1 | The spatial general equilibrium model

We use a large spatial dynamic general equilibrium model calibrated on a fully integrated system of SAMs for the 267 NUTS-2 regions of the EU and the United Kingdom, plus a residual region accounting for the rest of the World (ROW). In Appendix A and B, we report the full description of the model. All the regional economies are disaggregated into 10 NACE 2 sectors whose nested production structure considers three types of labor (low, medium, and high skill), capital, and intermediate inputs. The latter can either be supplied domestically or imported, with the trade flow data coming from the estimates of Thissen et al. (2019), who estimate the interregional trade flows using nonlinear programming techniques based on information on freight and passenger transport trips (note that these data control for the existence of logistic hubs). The model has involuntary unemployment modeled through a wage curve as in Blanchflower and Oswald (1994), implying that not only local wages but also employment will increase after a positive shock to the economy.

This spatial general equilibrium model contains mobile production factors. The responsiveness of migration to economic conditions is calibrated using EU intraregional migration data as described in Brandsma et al. (2014). Capital mobility is obtained through an investment decision model according to which the investment-capital ratio depends on the gap between the rate of return to capital and the replacement cost of capital (Uzawa, 1969). This rule ensures that all regions converge to the same rate of return to capital in the long run. Selected sectors are characterized by imperfect competition and economies of scale. The households featured in the model consume all the varieties of final goods available in the economy according to a constant elasticity of substitution (CES) function with love for variety across goods from different regions. Governments intervene in the economy with current expenditure, investment, and transfers to households, all financed via tax collection. Firms produce goods and services with a CES production function combining capital and labor, and intermediate inputs domestically produced or imported.

Given that the analysis focuses on transport costs, which have a direct implication for the prices of goods and trade flows, it is worth expanding on the part of the model dealing with trade. Goods and services can either be sold domestically or exported. In each region r and sector j a single Armington nest aggregates imports from all EU regions, including the region itself, and the ROW. We use a relatively high Armington elasticity, σ, of 4 to reflect that regions are necessarily more open than countries as they can hardly satisfy the internal demand solely with domestic production due to their size. The demand for sector j output supplied by region r to region r' then is given by

$$x_{r,r',j}N_{r,j} = \eta_{r,r',j}\frac{p_{r,r',j}^{-\sigma_j}}{P_{r',j}^{-\sigma_j}}X_{r',j}, \tag{1}$$

where $\eta_{r,r',i,}$ is a calibrated expenditure share, $X_{r',i}$ is the Armington aggregate in region r', while $P_{r',j}$ is defined as a CES price index over the market prices $p_{r,r',j}$ and $N_{r,j}$ is the number of firms in region r and sector j

$$P_{r',j} = \left(\sum_r \eta_{r,r',j}N_{r,j}p_{r,r',j}^{1-\sigma_j}\right)^{\frac{1}{1-\sigma_j}}. \tag{2}$$

We adopt a Dixit and Stiglitz (1977) formulation of the markup of firm-level product differentiation, such that the price $p_{r,r',j}$ charged by a firm of region r, selling to region r' is set at the optimal markup $\frac{\sigma_j}{\sigma_j - 1}$ over marginal cost $c^*_{r,j}$, including iceberg transport costs $\tau_{r,r',j}$ and production taxes τ^p_r, such that

$$p_{r,r',j} = \frac{\sigma_j}{\sigma_j - 1}(1 + \tau_{r,r',j})\left(1 + \tau^p_r\right)c_{r,j}. \tag{3}$$

The markup does not depend on the market shares or the number of firms. As a result, a single region sells products to all the other regions at the same free-on-board price, even if consumers in the importing regions observe different cost-insurance-and-freight prices, which are included in the iceberg transport costs. We assume iceberg transport costs given their standard use in trade and economic geography models. Under the iceberg assumption, transportation services are produced with the same production function as the industry producing the transported goods, avoiding the need to model a different transport sector explicitly.

The marginal cost includes the cost of production factors and the intermediate price index *PIN*,

$$c_{r,j} = a^v_{r,j}PY_{r,j} + a^{\text{Int}}_{r,j}PIN_{r,j}, \tag{4}$$

where $a^v_{r,j}$ and $a^{\text{Int}}_{r,j}$ are the share parameters attached to the value-added and intermediate inputs, respectively.

Equations (1) to (4) highlight how changes in transport costs enter the model. However, it is important to realize that the changes in transport costs and product prices will affect many other parts of the general equilibrium model. If a region faces lower transport costs, it can source intermediate inputs at a lower cost, and its firms will become more competitive in their export markets. Demand for its products will increase, leading to higher labor demand, higher wages, immigration and investment, and higher local income and demand. There will be endogenous adjustments in the spatial distribution of upstream and downstream firms through investment and population through migration. The general equilibrium model captures all these mechanisms.

3.2 | Baseline structure of European regional trade

The share parameters $\eta_{r,r',j}$ in the trade equation (1) are calibrated to observed international trade flows that have been regionalized by Thissen et al. (2019). These parameters reflect the structure of interregional trade and are an important determinant of the estimated effects of the transport infrastructure policies we present below. As an illustration of the structure of interregional trade in the EU, we focus on trade between "Western European" and "Eastern European" regions.[3]

Figure 1 illustrates the regional trade intensity of each Western European region with Eastern Europe as an aggregate. We define this intensity as the sum of exports and imports to/from all Eastern European countries, relative to the regional GDP. On average, the trade intensity decreases as the distance to Eastern Europe increases. Most of the highest values (up to 7.4% of GDP) are recorded for regions geographically close to the Eastern European regions, but there are several exceptions. Given this nonsmooth geographical distribution of trade flows, we may expect the spillovers of any transport infrastructure policy targeting Eastern Europe to be unevenly distributed as well.

[3]For the sake of brevity, in this paper, we often refer to all formerly communist EU countries, which are major recipients of ECP funding as "Eastern Europe," although perhaps Central and Eastern European would be more precise. We refer to the other EU countries as "Western Europe," although, for instance, Greece is clearly one of the most eastwardly located EU members.

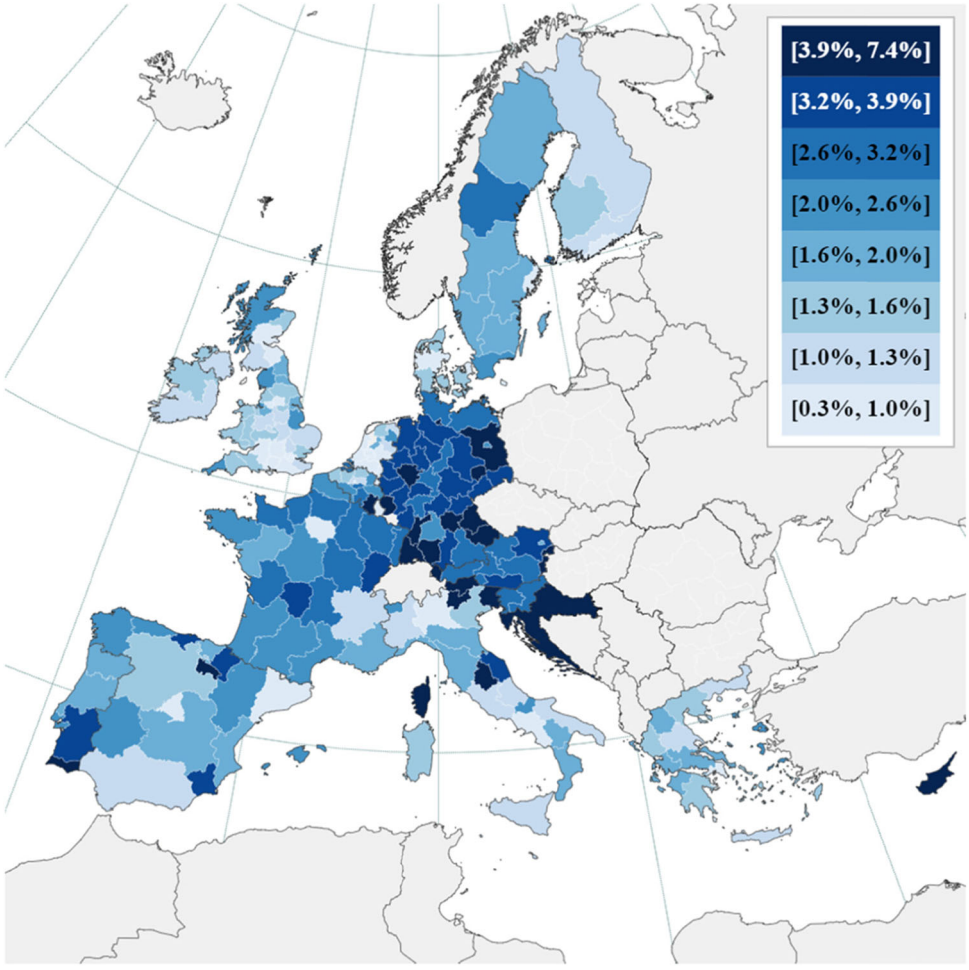

FIGURE 1 Regional trade intensity with selected Central and Eastern European countries.

3.3 | Baseline transport costs

For the calibration of the transport costs $\tau_{r,r',j}$ in Equation (3), we use the methodology described in Persyn et al. (2022). We start by taking large samples of centroids from a 1 km^2 resolution population grid. We define the GTC as the lowest cost of a 40-tonne truck trip between the centroids over a detailed digitized road network (OpenStreetMap—see Figure C1 in Appendix C), averaged at the region-pair level. The costs that are related to the truck and the trip are fuel costs, the driver's wage, maintenance costs, insurance, taxes, road tolls, speed limits, and orography-related ones. The model does not include costs related to storage, cooling, or handling of goods.

The sampling approach with many origins and destinations per region allows the estimation of transport costs between and within individual regions. It is important to obtain an estimate of transport costs within each region since, on average, 75% of regional output remains within the region (where it is either consumed in the private or public sector, or used as intermediate or investment good). The ratio of internal to external transport costs therein is an essential determinant of how changes in transport costs affect the economic activity.

Our general equilibrium framework requires considering transport costs in the ad-valorem iceberg-type transport cost form, where transport costs are expressed proportionally to the value of the shipped goods.[4] We use the sector-specific average value–weight ratio to approximate the number of trucks required to ship the observed amount (value) of goods between regions to get the iceberg transport costs (following Hummels, 1999; Zofío et al., 2020).

The GTCs in monetary units are transformed into iceberg costs as follows:

$$\tau_{r,r'} = \frac{F_{r,r'}\left(\frac{1}{L}\right)GTC_{r,r'}}{V_{r,r'}} - 1, \tag{5}$$

where $\tau_{r,r'}$ is the iceberg transport costs from region r to r', $F_{r,r'}$ is the flow of goods in tons, $GTC_{r,r'}$ is the average GTC between both regions, in EUR per truck, and L is the EU-wide average loading of trucks, equals to 13.6 tonnes per truck, and $V_{r,r'}$ is the total value of the flow of goods from r to r'. Finally, the average weight-value ratios $\left(\frac{F_{r,r'}}{V_{r,r'}}\right)$ are adjusted from free-on-board to cost, insurance and freight prices using the International Transport and Insurance Cost of Merchandise Trade database from the organisation for economic co-operation and development.

3.4 | Soft-linking a transport cost model

3.4.1 | Counterfactual transport costs: Cohesion policy

We now investigate the effects of large-scale transport infrastructure improvements on economic outcomes and the spatial distribution of economic activity using the combined model. As a case study, we consider the effect of the road transport infrastructure investments of the 2014–2020 ECP program, amounting to about €30 billion. These ECP investments are mainly destined for the peripheral countries and regions of the EU, as shown in Figure 2 below. It is important to emphasize that the geographic distribution of funds at the NUTS-2 level is exogenously given by the ECP, and it is not a choice made by us or the model. What we estimate is which specific road segments are selected for upgrading, given the investments destined for the various regions of the EU. The first goal is to calculate the change in transport costs between regions due to the investment, which then is then used in the general equilibrium model.

We use a cost–benefit analysis based on Persyn et al. (2022) to select the roads that are improved for a given investment amount in a region. The cost–benefit approach starts by estimating the amount of traffic on each road segment considering the trade flows between all EU regions from Thissen et al. (2019). Specifically, in an auxiliary analysis, a gravity equation is used in combination with a geographic information system to project the given trade data for each region-pair on the local road network, to impute the number of trucks driving on all road segments on the lowest-cost route connecting each sampled centroid-pair. Many centroids are sampled per region, making this a computationally intensive exercise. We then calculate the gross aggregate economic gain from upgrading the road to a highway, by taking the total estimated traffic on the road and calculating the difference in the cost corresponding to this traffic, given the properties of the road before improvement and after improvement. This gross gain is then compared to an estimate of the cost of highway construction. This cost is taken to be €10 million/km (Jacobs-Crisioni et al., 2016), and it is adjusted by the price index for civil engineering works on the country level and by additional penalties depending on the population density of the immediate surroundings of the roads, and the slope of the terrain. To summarize, we assign the given level of trade at the region-pair level to individual road segments to identify which segments would produce the largest economic gain

[4]We assume an iceberg-type transport cost for tractability purposes, and to ease the link between the spatial general equilibrium model and the transport model. For an in-depth discussion on the trade-off between realism and tractability of transport costs, see McCann (2005). Bosker and Buringh (2020) provide an empirical assessment of iceberg-type transport costs.

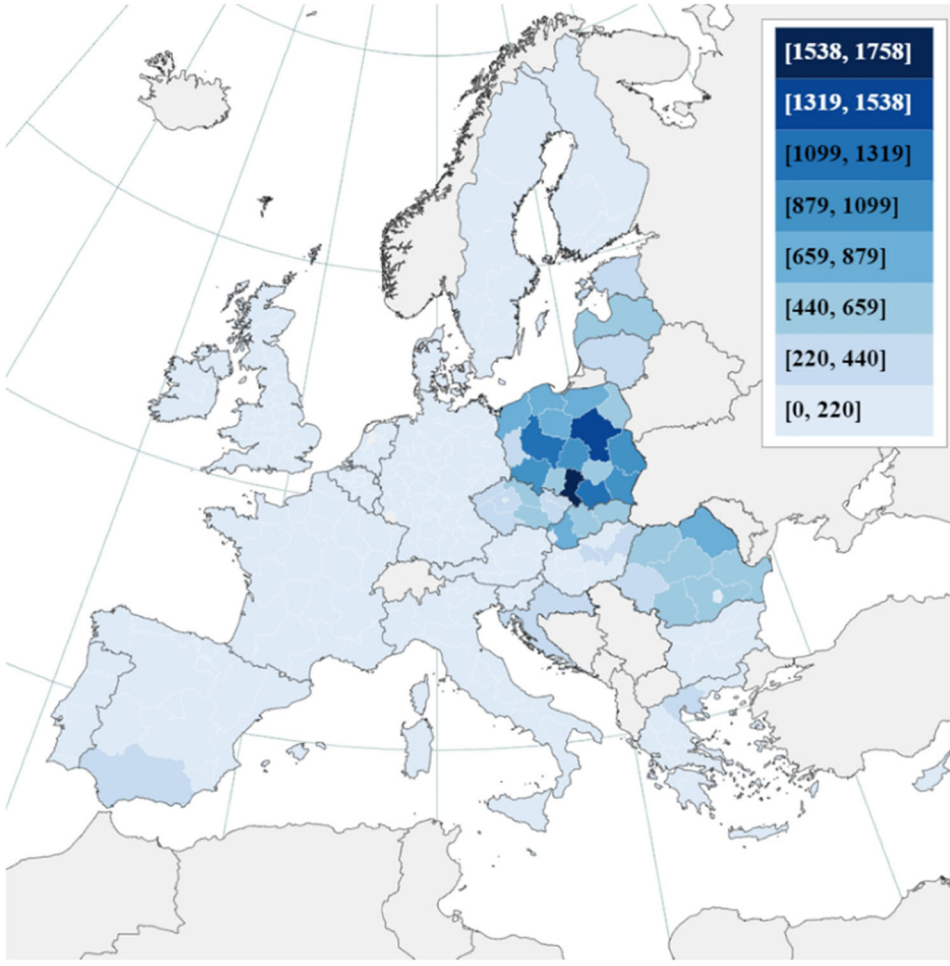

FIGURE 2 Given European Cohesion Policy investment (in millions of €) in road transport infrastructure for the years 2014–2020. *Source*: European Commission (DG REGIO).

when upgraded. After ranking the segments by the net gains from improving the road within each region, we assume that the improvements target the roads with the largest benefits until the funds assigned to the region are depleted.

The left panel of Figure 3 shows the primary and secondary road segments (highways are excluded) that have been selected for improvement, given the regional investments from the ECP. The road improvements are clearly concentrated in Eastern Europe, where most investments are taking place. Note also that this concentration is even higher in terms of the total length of improved roads, given the lower price index for civil engineering works in Eastern Europe compared to central Europe or, for example, Italy.

The construction of a highway at or near the identified bottleneck on the selected routes is simulated by increasing the maximum speed for trucks to 90 km/h and by removing all speed penalties related to intersections, traffic lights, and roundabouts. We can then calculate a counterfactual transport cost matrix that reflects the reduction in transport costs due to the transport infrastructure investment. To give some intuition on the effects, we find that the improvements reduce the driving time for trucks from the North-East to the North-West of Poland from 11.7 to 10.7 h, or by about 10%. The resulting reduction in transport costs is estimated to be about 3.3%.

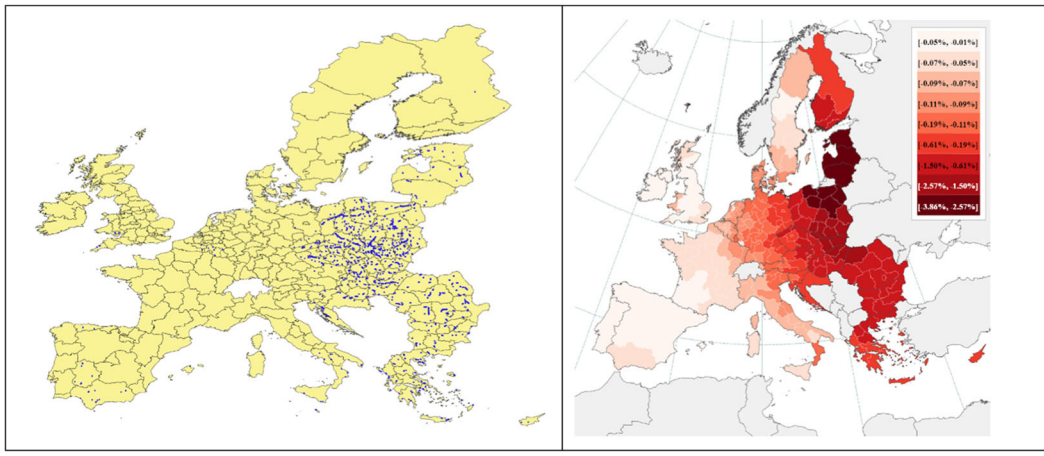

FIGURE 3 Left: Roads selected for improvement by the cost–benefit. Right: Estimated decrease in the harmonic weighted average transport cost.

The right panel of Figure 3 shows the resulting estimated impact of the policy on the transport costs in the EU at the regional level. Due to the investment, each region potentially experiences a change in the transport cost internally and with its 266 regional trading partners. To plot the changes in transport costs on a map, we consider, for each region, the change in the harmonic weighted average of the trade costs to all regions.[5]

The impact of the investment is, on average, higher in the Eastern European regions targeted by the policy, but there are some interesting exceptions. First, Finland, the Baltic countries, and Northern Poland experience relatively large decreases in the average transport cost compared to the local investment (comparing Figure 3 to Figure 2). This is due to their location along a corridor benefiting from investments, running through the Baltic region over Northern Poland, and connecting them to the European economic core regions. A similar mechanism is at work in Bulgaria and Greece, which benefit from investments in, for example, Romania, Hungary, Slovakia, and Southern Poland, improving their connectivity to the European economic core regions without receiving much investment. The spillovers in Eastern Germany and Austria are notable. It is important to consider the scale when considering these spillovers. The spillover effects from the policy on the average transport costs in Eastern Germany are about one order of magnitude smaller than the direct and indirect effects in the targeted areas in Poland. The average effect reported in the figure hides that trade costs toward some destinations may substantially decrease, while trade links to other destinations are not affected, and this asymmetry is more pronounced in the regions that are not directly targeted.

Our approach allows studying arbitrary amounts of investments in any region and not only known infrastructure investment projects, similar to what has been done by Allen and Arkolakis (2022) and Blouri and von Ehrlich (2020). The latter authors consider an iceberg transport cost matrix based on travel times throughout the European road network and assign probabilities for shipping goods shipped between adjacent regions and those passing through. In their framework, transportation infrastructure reduces travel times between all possible direct links within the road network. Our approach, in contrast, differs from Blouri and von Ehrlich (2020) by considering a detailed road network. In our model, transport infrastructure investment is subject to decreasing returns as subsequent investments improve roads that are lower on the cost–benefit list. Depending on the location of the improved road link, infrastructure investment may lower transport costs with only specific trade partners and not with others. Moreover, our approach considers that the composition of transport

[5]Figure 3 shows the estimated percentage drop in the harmonic average GTC of each region relative to all others, weighting partner regions by their regional value added. As argued by Head and Mayer (2010), Hinz (2017), and Persyn et al. (2022), the harmonic average will heavily weigh changes in transport costs at close distances, for nearby regions, for which there is more trade. Therefore, the change in the harmonic average trade cost rather than the arithmetic average is a better predictor of changes in trade flows.

costs and the effect of investments will differ between localities, depending on infrastructure prices, wages, fuel prices, tolls, and the other factors considered in the analysis (as described in Section 3.3).

3.4.2 | Local linear approximation

The calculation of counterfactual transport costs consists of two computationally intensive steps. First, we calculate the total traffic over each of the four million road segments to rank them for the cost–benefit analysis, and then compute the transport costs between many sampled centroids before and after improving the selected roads. To save computing time, we suggest a local linear approximation and regional decomposition of the estimated reduction in transport costs. The procedure starts by considering the ECP investments in every region separately and calculating the matrix of reductions in transport costs between all pairs of EU regions caused by the investments in this region alone. Denote by D_k the 267×267 matrix containing the predicted relative changes in transport costs between all region pairs caused by the ECP investment I_k^{ECP} only in region k, where k indexes over the 267 EU regions in the model. The 267×267 matrix of the total change in transport costs Δ between all region pairs, due to a set of regional investments in road infrastructure of size I_k (which may deviate from the ECP investment that was used for the calculation of D_k) in each region k, is approximated by

$$\Delta = \sum_{k=1}^{267} \frac{I_k}{I_k^{ECP}} D_k. \tag{6}$$

Calculating the D_k matrices involves solving the full computationally intensive transport model 267 times, once for each region. However, once the set of 267 matrices D_k, each of size 267×267, has been calculated and stored, Equation (5) can be used as a linear approximation, which computes in milliseconds, compared to many hours for the full model. We find that the correlation between the predicted change in the transport costs when using the full simulation and the local linear approximation is above 0.99.

The matrices also offer a summary of how each region connects to the other EU regions. As an example, Figure 4 shows a heat map representation of a single matrix D_k, showing the effect of investments in the Northern Polish region Podlaskie (PL34) alone. This region is likely to be crossed by a truck going from the Baltics or Finland to Western Europe or vice versa, but hardly by any other trip (say from France to Spain). This is visible from the heat map, which is quite sparse, and only shows reductions in transport costs for the three Baltic countries, Finland, two Polish regions (PL34 itself and its neighboring region PL62), and the most Northern Swedish region SE33, which borders Finland. Key features from geography are reflected in the matrix. Notice, for example, that the lines of Finland and Estonia do not cross (because investment in a Polish region does not affect trade costs between them), although the accessibility of Finland and Estonia to many EU regions benefits from investment in Podlaskie (PL34). The improvement in connectivity mainly benefits other Polish and European regions, such as the neighboring Baltic country of Lithuania, and more northern countries and regions.

For some central regions along important corridors, investments would lead to significant changes in transport costs between many other origins and destinations. Other more peripheral regions may experience significant decreases in their internal transport costs, but hardly affect trade costs in the network.

4 | THE MACROECONOMIC EFFECTS OF ROAD TRANSPORT INFRASTRUCTURE INVESTMENT

This section uses the spatial general equilibrium model with the soft-linked transport model to simulate how various economic variables are affected by the reduction in transport costs induced by the regional road transport infrastructure investments of the 2014–2020 ECP programs.

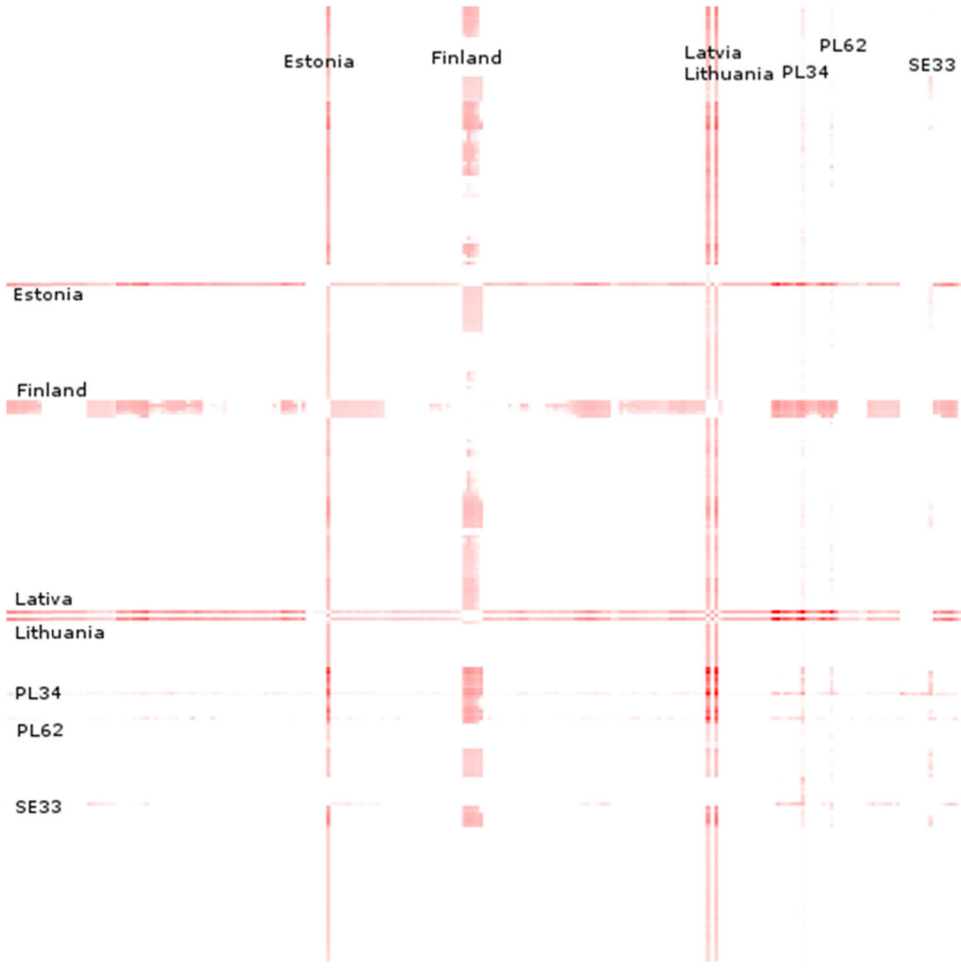

FIGURE 4 Heat map of the changes in transport costs due to investments in Podlaskie (PL34) in the North-East of Poland.

The shock to transport costs is built up over 10 years (corresponding to a single ECP programming period), and the general equilibrium model is then run forward until the new long-run equilibrium is achieved where the capital stock in all sectors has fully adjusted, and there is no more net migration between the regions. Unless mentioned explicitly, we ignore demand-side effects such as the taxes that need to be raised to fund the policy, or the effects of the local expenditure on materials and workforce required to build the roads. Likewise, we do not consider indirect effects such as an impact on regional productivity. We instead focus on the long-run supply-side effects directly resulting from the decrease in transport costs, such as changes in the relative competitiveness of firms in different regions, changes in the cost of living, and changes in the spatial equilibrium distribution of labor and capital. Our model operates at the NUTS-2 level, and we ignore commuting and congestion, which may be more important at smaller spatial levels such as cities (Vandyck & Rutherford, 2018).

Iterating between the transport and the general equilibrium model to endogenize wages in the transport costs estimation has a negligible impact on the results, and we therefore report the results of a single-step analysis, feeding the transport cost change to the spatial general equilibrium model, but not back. The reason is that most of the effect of the policy operates via lower prices, and changes in nominal (as opposed to real) wages are very small.

4.1 | Effect on trade patterns

The reduction in transport costs lowers the prices of final and intermediate goods, thereby increasing the quantity demanded. Regions receiving a large investment in relation to the size of their economy may be expected to increase trade with other EU regions and with the ROW, where commodity prices and transport costs are held fixed. Also, regions where no transport infrastructure investment is taking place experience changes in the relative prices of their exports and imports with the regions where the investments take place, giving rise to complex system-wide impacts. Over time, interregional links via labor and capital mobility also affect the overall effect of the change in transport costs.

We first consider the effect of reduced transport costs on exports. Figure 5 shows the long-run percentage change in per-capita exports in each region, which is positive in all regions. As expected, large increases in exports are observed in the regions targeted by the policy, which are concentrated in Eastern Europe. We also observe regions, mainly located in Finland, Greece, and, to some extent, France and Germany, enjoying increases in exports despite receiving few or no ECP investments in transport infrastructure. Interestingly, the United Kingdom is only marginally affected, apart from a few regions in the North-East of England. The Netherlands, the North-West of Italy, and the Castilla-La Mancha region of Spain are almost unaffected, with effects below 0.001%. In general, the magnitude of the effects tends to diminish when moving away from the regions especially targeted by the policy. These spillover effects from the investment in Eastern Europe are studied in more detail in Section 4.3. Moreover, the increase in exports follows the geography of the decrease in transport costs in Figure 3 more closely than the geography of investments in Figure 1. These findings illustrate the importance of considering the geography of trade and transport in a dedicated transport model, which can then be combined with a spatial general equilibrium model, as we do here.

4.2 | Effect on the spatial distribution of labor, GDP, and welfare

Figure 6 shows the long-run effect of the ECP road transport infrastructure investments on migration (left panel) and regional real GDP per capita (right panel). The modeling of migration in the model is explained in Appendix A and Equation (A33). Migrants are assumed to become indistinguishable from the local population after their arrival.

The decrease in transport costs leads to a net reallocation of workers toward the regions targeted by the investments. Allowing for labor mobility across the EU regions magnifies the macroeconomic effects of transport investments in Eastern European regions. As the current situation is one of net migration from Eastern Europe, the ECP may act to retain some local workers, a pull factor that makes low-income regions relatively more attractive despite the initial productivity gap. However, the numbers are relatively small: for instance, the regions with the largest changes in the labor supply are Śląskie (PL22) and Eastern Slovakia (SK04), both reporting a 0.2% increase in the labor supply from initial base year values associated with investments amounting to 6% and 7% of their local GDP, respectively.

Negative net migration appears in Germany, Austria, Sweden, and South England. However, the decrease in the labor supply (and possible impact) in those regions relative to the baseline is small. The limited effect of the policy on migration may be caused by our parameter estimates governing migration behavior, which take into account the presence of international borders as hurdles to migration (see Equation A33 and the discussion on migration in Appendix A). Moreover, by modeling labor market imperfections, we allow decreasing local unemployment to partially meet the higher local labor demand due to policy intervention. Thus, there may be less need for migration. This can lead to more localized effects compared to a model where any increase in the local workforce must necessarily stem from immigration.

Adding all the changes in regional GDP for Poland gives an increase of about €767 million/year. This compares to an investment of almost 15 billion in the country. There are spillovers to other regions. A country like Austria, for

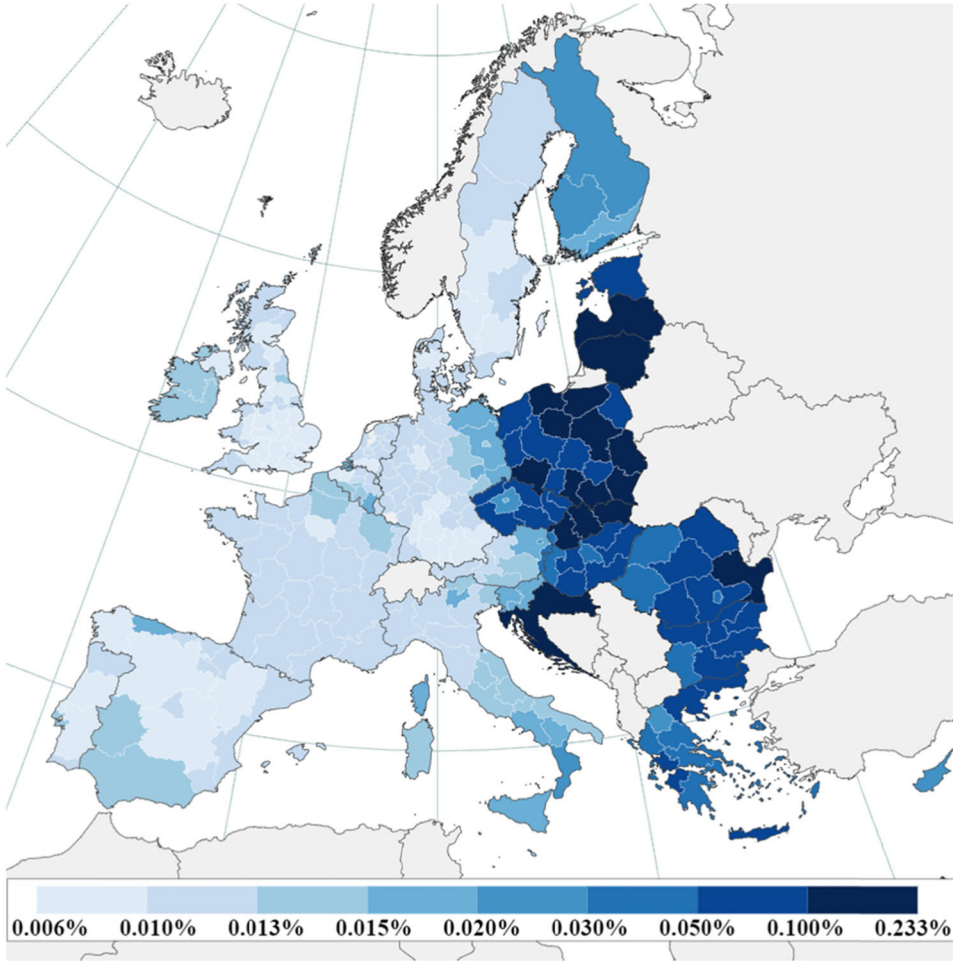

FIGURE 5 Changes in total exports per capita due to European Cohesion Policy road improvements (% differences from the baseline values).

example, enjoys a relatively large increase in regional GDP, although it hardly receives any funds. The GDP of the EU as a whole is projected to increase by €1.23 billion/year in the long run. This compares to an investment of about 30 billion. It might be tempting to interpret this as an investment requiring about 24 years to pay off. However, this number ignores all demand-side effects, including the fact that some of the funds would flow back immediately to the government in the form of taxes, and it also ignores benefits such as decreased commuting time or increases in productivity. Moreover, a key objective of the ECP policy is to reduce inequality rather than to produce an economic return. Our simulations suggest that the additional transport infrastructure Central and Eastern Europe does not lead to a relocation of the capital to the economic core of the EU, and the largest benefits accrue to the targeted regions, although some spillovers exist. The latter are especially large in regions that are mostly outside the economic core of Europe, such as Eastern Germany, Greece, and Northern Finland.

Aggregate regional GDP increases by up to 0.4% in some Eastern European regions and decreases slightly (by at most 0.017%) in some Western regions. Labor mobility attenuates these losses in GDP, as shown in the right panel of Figure 6, which highlights that GDP per capita increases everywhere in the long run. We focus on variables expressed in per-capita terms in the remainder of the analysis. A cross-sectional regression with the change in

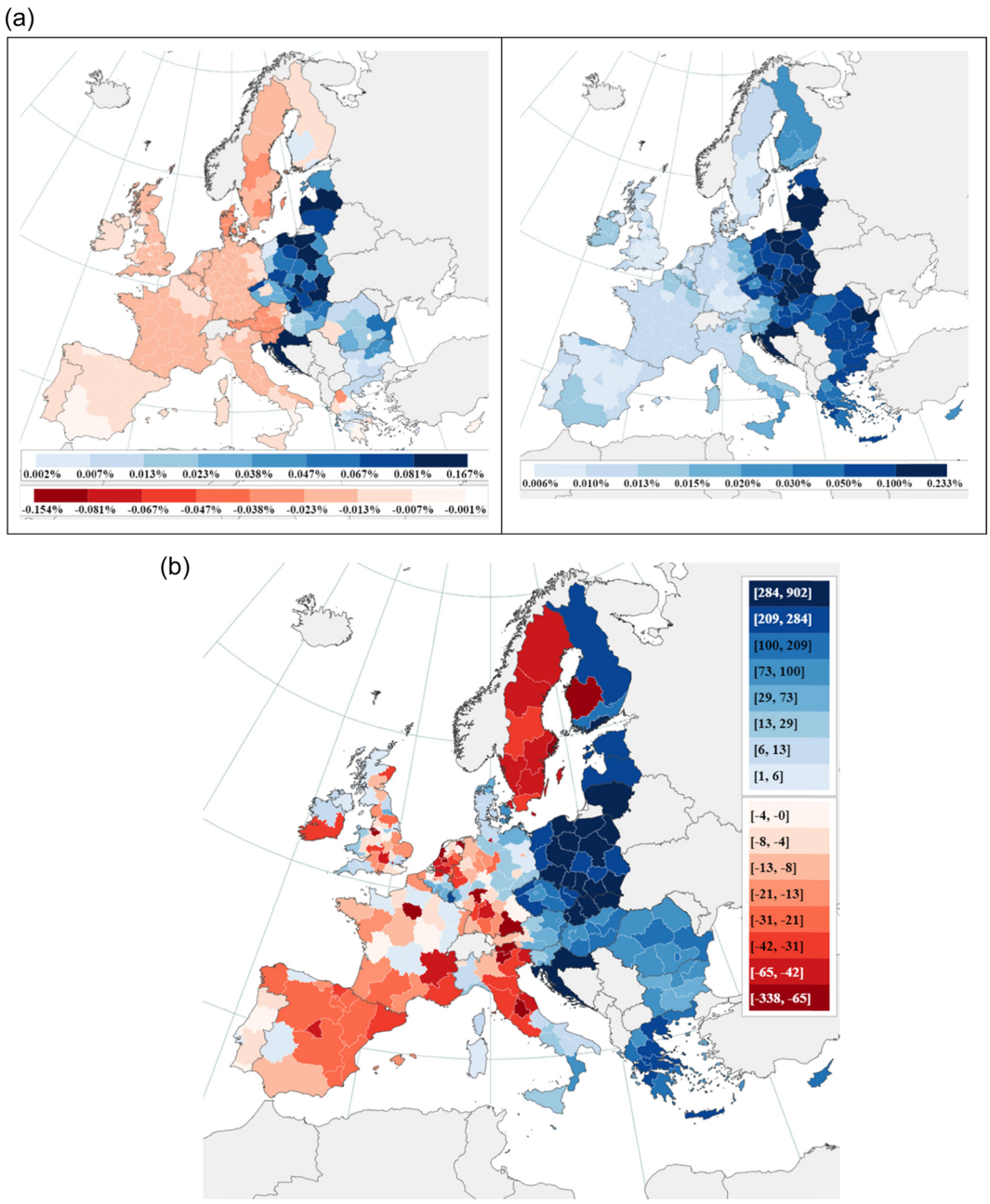

FIGURE 6 (a) Left: Change in labor force due to internal migration. Right: Change in real gross domestic product per capita. (b) Money-metric change in per-capita welfare.

per-capita GDP as the dependent variable indicates that a high regional unemployment rate may double the impact of the transport infrastructure investments on the local GDP. More details are given in Appendix C.

We now offer a basic cost–benefit calculation of the policy. We calculate the system-wide gains of the transport infrastructure improvements associated with the 2014–2020 ECP as the cumulative sum over 50 periods of the discounted present values of the changes in GDP net of the discounted present values of the actual

disbursements that regions must make to finance the investments (assumed to be proportional to the share of regional GDP over the EU GDP). Our calculations suggest that the average per-capita net gain for the EU is around €62. There is significant heterogeneity across regions and countries, with Eastern regions gaining about €244 per capita, while the per-capita net benefits for the rest of the EU are lower, at €19 on average. This confirms the finding that not only the targeted regions benefit from the ECP transport infrastructure investments but also the rest of the EU economies, essentially through trade spillovers. Therefore, albeit contributing more, richer regions still benefit from investments taking place elsewhere.

Besides looking at the impact of the policy on GDP, we also consider a measure of the change in consumer welfare, in monetary terms. More specifically we consider

$$\Omega = \sum_{t}^{T} \frac{1}{(1 + disc\_r)^t} \left[\left(\bar{C}_t - P_t^c \bar{\bar{C}}_t \right) + \left(P_t^c \tilde{C}_t - \bar{C}_t \right) - c_t \right] = \sum_{t}^{T} \frac{1}{(1 + disc\_r)^t} \left[P_t^c (\tilde{C}_t - \bar{\bar{C}}_t) - c_t \right], \tag{7}$$

where $\tilde{C}_t$ denotes per-capita consumption at period t after the transport infrastructure improvement shock, $\bar{\bar{C}}_t$ is the baseline per-capita consumption, and P_t^c is the consumer price index at period t (and $P = 1$ in the baseline).

This measure is a compensating variation (CV) measure of welfare (Chipman & Moore, 1980; Hicks, 1942). Often only the first term in round brackets is used, which considers a price effect: it expresses the decrease in the budget that would allow to reach the old level of consumption at the new (in our case mostly lower) price level. This measure is incomplete in our application, as many other variables such as wages are changing in our simulations, implying that consumer welfare may change even with constant prices ($P_t^c = 1$). The second term in round brackets corresponds to the additional per-capita household expenditure that is observed in the counterfactual, the income effect (see also Atkin et al., 2018; who further decompose this term). The last term, c_t, is the cost of the project in per-capita terms, where costs are shared between all EU regions proportionally to the regional GDP. The second equation shows that this can be simplified as the difference in per-capita consumption between the policy scenario and the baseline, evaluated at the counterfactual prices (a Paasche index), net of per-capita costs, which is a quite intuitive measure of consumer welfare in monetary terms. The improvement in transport costs and the costs are spread proportionally over the first 10 years of the simulation.

Figure 6b shows the results at the regional level, using a discount rate (*disc_r*) of 3%. We see that the policy increases consumer welfare in monetary terms in Eastern Europe, by about €100–600 in present value terms, with outliers up to €900 in the most affected regions. Although, in the long run, GDP per capita increases in all regions, discounting future changes and taking into account the cost of the project implies that many regions outside the targeted area lose, by about €50–100 with some outlies to €200–300. Finland and Greece, as well as regions that are relatively low income (and therefore do not contribute as much to the cost) and/or trade intensely with Eastern Europe benefit, such as Eastern Germany, but also the South of Belgium and the South of Italy. These outcomes depend greatly on the discount rate. With a discount rate of 2%, all EU regions gain. With a discount rate of 4%, almost no region outside the targeted areas of benefits (with the exception of Finland and Greece). It has to be emphasized that our analysis excludes some mechanisms that are likely to add to broader definitions of welfare gains, such as improvements in commuting time, or increases in consumption by the government which is a part of GDP but not considered in this welfare measure.

4.3 | Spillovers and the ripple effects

As we showed in Figure 2, the 2014–2020 ECP road infrastructure investment is largely concentrated in Eastern Europe. The results considered so far suggest that these investments generate positive spillovers to other regions of the EU. The study of these spillovers is complicated by the fact that there are limited investments in some neighboring regions, such as Eastern Germany, or more peripheral regions in, for example, Italy and Spain. To study the effects of spillovers in isolation, we therefore consider an alternative "Spillover" scenario, considering only the

transport infrastructure investment in Eastern European countries, setting the investments in all other regions at zero. In this scenario, any economic effect observed outside of Eastern Europe is therefore a spillover and not a direct effect. The changes in the matrix of transport costs are recalculated according to the method explained in Section 3.4.2. Figure 7 shows the resulting long-run regional differences in per-capita GDP from its base year values for the regions not receiving any funds.

These effects are not uniformly distributed across the regions not receiving funds. They lie between +0.006% and +0.033%, with a standard deviation of about 0.01. There appears to be only a weak spatial gradient in the spillovers. The effects are larger in the regions closer to Eastern Europe, and they tend to be negatively correlated with distance from the shocked regions (with some exceptions like, e.g., two regions in the South of Portugal and Ireland). These deviations correlate with the intensity of trade links with Eastern Europe, as shown in Figure 1. A similar finding is offered by Thissen et al. (2020) in an analysis of the economic implications of Brexit, in which the influence of trade links is not necessarily monotonously decreasing with geographical distance.

Regions may be affected differently by the policy for a variety of reasons, such as the sectoral and spatial composition of their trade links. The large positive effects seen in the heavily industrialized and densely populated

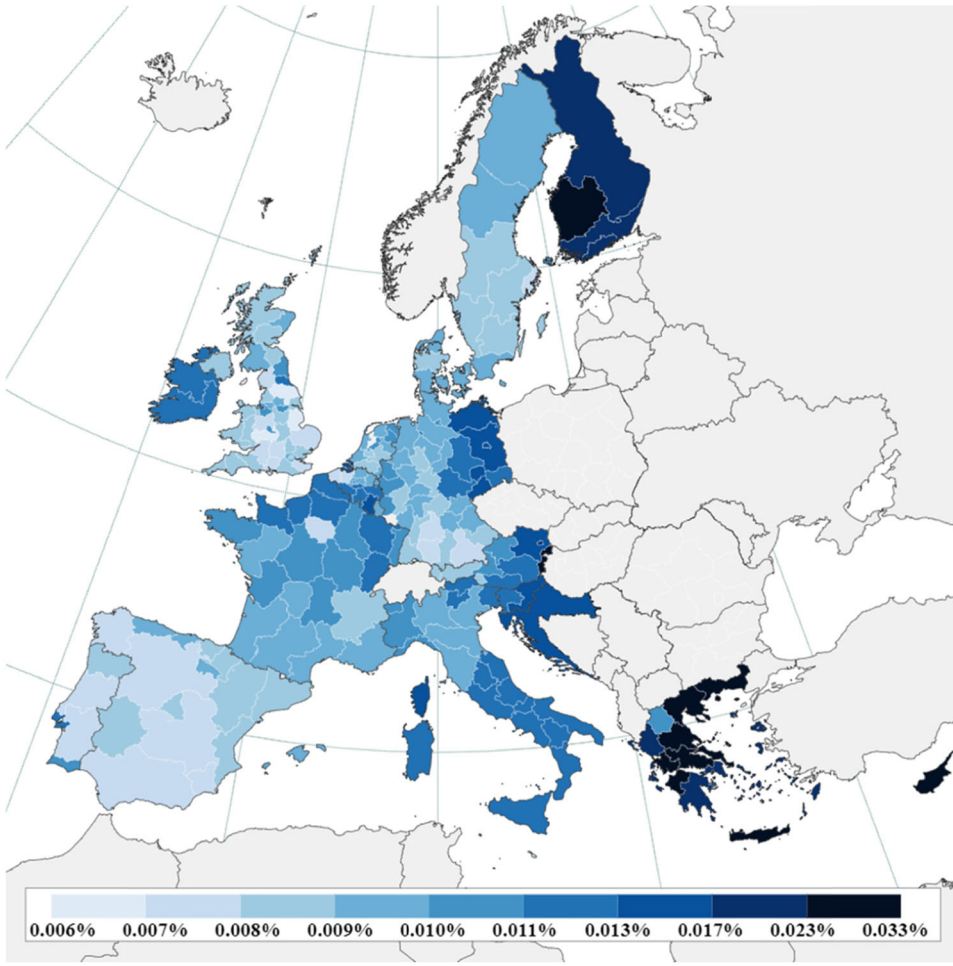

FIGURE 7 Long-run changes in regional gross domestic product per capita (noncumulative)—Spillover scenario.

Western German Ruhr and Saar regions, compared to Southern Germany, are likely due to a trade mix that is more heavily geared toward the export of manufacturing goods, with trade links that span over large distances.

Although Figure 7 shows that the idiosyncrasies influencing regional spillovers are large, some important regularities exist. First, some national borders are clearly visible on the map. For instance, the regions on the eastern borders of Germany, France, Northern Italy, and Austria experience stronger spillovers compared to the other regions of these countries. That borders play a role is unsurprising given that there are many types of boundaries (legal, procedural, cultural, linguistic) that imply that borders continue to be hurdles to trade, and this is reflected in the interregional trade data by Thissen et al. (2019), which is used in the model calibration. How could it be, however, that the economic benefits of road infrastructure investment in Eastern Europe are larger in the North-East of France compared to the bordering regions in the South and West of Germany? A priori, it would be more intuitive to see larger spillovers in South-Western Germany, which is closer to Eastern Europe.

The mechanism at work here may be related to trade creation and diversion, in a context with multiple trading partners and asymmetric changes in trade costs due to geography and border effects. See, for example, the discussion on the effects of preferential trade agreements in Baldwin and Wyplosz (2019), explaining how asymmetric changes in trade costs come with gains and losses for different locations (and the empirical evidence presented by Baum-Snow et al., 2020; Faber, 2014). Although all regions experience a decrease in trade costs with Eastern Europe, this is more relevant for regions which, within the country, are closer to Eastern Europe because their trade volume with Eastern Europe is larger, on average, compared to other regions within the same country. A possible channel which we will consider below using regression analysis is the following: through cheaper imported intermediates from Poland, regions in Eastern Germany become more competitive relative to other German regions, and therefore all German regions may substitute imports from, say, Southern German regions for the now cheaper imports from East Germany. These Southern German regions would then face a decline in the demand for their exports. Such within-country import substitution patterns would be more important the larger the international border effects on trade flows are and may explain why we see a spatial gradient within countries.

The emergence of these "winners" and "losers" within countries can be seen in Figure 8 for two German regions of Mecklenburg Vorpommern (DE80) and Tübingen (DE14) and the two French ones of Lorraine (FR41) and Rhône-Alpes (FR71). In both cases, one region is located close to the Eastern border (DE80 and FR41 for Germany and France, respectively), and the other is relatively far from it, in the South (DE14 and FR71).[6] For each of these regions, we consider the change in the geography of their exports to all other regions. These region-specific changes in exports are plotted in Figure 8 and can be considered in combination with the GDP effects experienced by the region solely due to spillovers, as reported in Figure 7.

We can clearly see that Mecklenburg Vorpommern (DE80; Figure 8a) increases exports to Eastern Europe but also to almost all other German regions. The increase in exports to regions in other Western European countries is also positive in most cases. On the other hand, Figure 8b shows the change in the spatial pattern of exports for the Southern German region of Tübingen (DE14). This region is relatively far from the Eastern European regions where all the transport infrastructure investments take place. Whereas the region enjoys an increase in exports to Eastern Europe, it faces a decrease in its exports to many other German regions and smaller decreases in exports to Western Europe. The decrease in exports from Tübingen to other German destinations is strikingly different from the increase in exports to other German regions experienced by Mecklenburg Vorpommern in Figure 8a.

Furthermore, the spillover effects on GDP reported in Figure 7 highlighted a specific pattern within France, suggesting that regions in the North-East benefit from proximity to Eastern Europe and experience an increase in competitiveness relative to other French regions. Figure 8c shows the change in exports of the North-Eastern French region of Lorraine (FR41), which is able to increase exports to many regions in Western Europe compared to

[6]See Figure C2 in the appendix for the exact location of these regions.

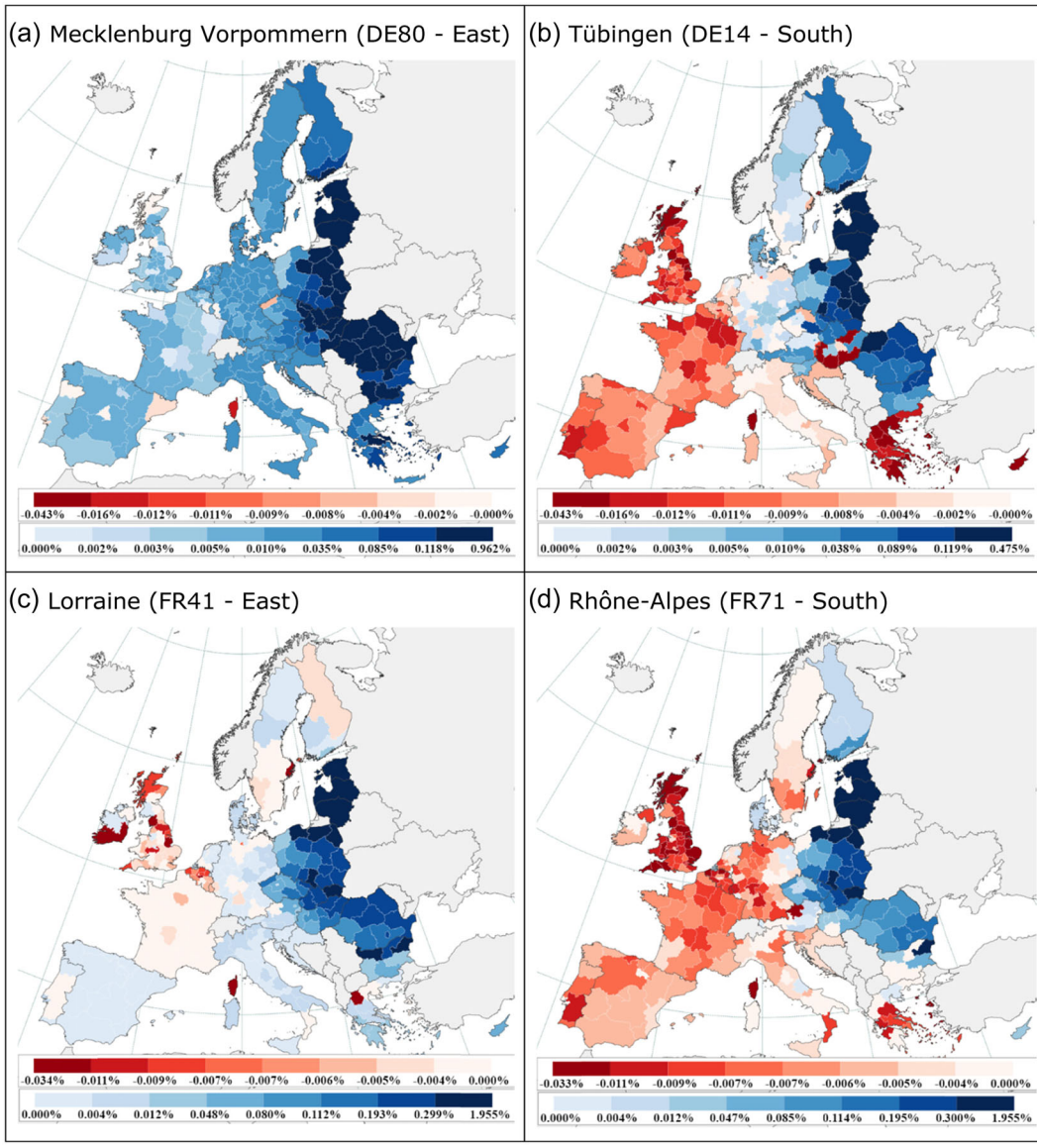

FIGURE 8 Changes in exports per capita of four regions (two German and two French).

the Southern region of Rhône-Alpes (FR71; Figure 8d), which loses export shares in many regions in France and abroad.

We now analyze these suggested determinants of spillovers using regression analysis. We use as the dependent variable the spillovers measured as per-capita GDP changes in percentage terms. In a series of increasingly richer model specifications, we consider the following potential explanatory variables: the weighted average distance from the regions of Eastern Europe (*distance_east*, in logs); the change in the weighted harmonic average in transport costs of the region (*TCost_change*); and the baseline trade exposure to Eastern Europe, calculated as the sum of imports from and exports to the Eastern EU regions relative to the regional GDP (*trade_east*). We also investigate the latter variable separately for exports and imports (*exp_east* and *imp_east*, respectively). Finally, we control for trade intensity with all trade partners

(*exp* and *imp*), and for the economic conditions of the regions by adding the unemployment rates (*unemprate*) to the right-hand-side variables of the cross-sectional model estimated with ordinary least squares.

The results in column (1) of Table 1 confirm the intuition that, on average, regions at a larger weighted geographic distance from Eastern Europe enjoy smaller spillovers in the form of increases in GDP. There is a spatial gradient in the spillovers and the western regions that are 10% farther from Eastern Europe experience about 0.002% smaller increases in GDP. This spatial gradient is very small in magnitude compared to, for example, the elasticity of −0.07 found by Banerjee et al. (2020). It has to be noted, however, that the distances we are considering here are much larger than that in Banerjee et al. (2020). If we limit the sample to regions with an average distance to Eastern Europe smaller than 800 km, the coefficient changes to −0.051 from the original −0.002. Taken together, this confirms what was already apparent from Figure 7: there are localized spillovers close to Eastern Europe. At larger distances, there are important idiosyncrasies in the spillovers that seem unrelated to distance, but rather to more complex regional trade patterns. Column (2) further investigates these patterns by replacing distance with an economically more meaningful measure: the baseline trade intensity with Eastern Europe (*trade_east*), defined as the sum of imports from and exports to Eastern Europe; and the change in the harmonic average transport cost of the region (*TCost_change*). The effects of trade intensity and especially the change in the weighted average transport cost have the expected sign, but only the effect of the coefficient of the change in transport cost is significant. The weighted change in transport costs has high predictive power, as seen from the large increase in the R^2 compared to the specification in column (1).

It is perhaps surprising that the trade intensity with the east is not important in explaining spillovers. This result changes when adding country fixed effects to this version of the model (see column (3)). The effect of the baseline trade intensity with Eastern Europe then becomes highly significant: within countries, regions trading more intensively with Eastern Europe benefit more than regions with a lower trade intensity with Eastern Europe. Lastly, column (4) of Table 1 separately considers import and export trade intensity. We differentiate between export intensity defined as exports relative to local GDP (*exp*), import intensity equal to imports relative to GDP (*imp*), and the same variables when only considering imports and exports to Eastern Europe, *imp_east* and *exp_east*. The results

TABLE 1 Regression analysis of spillover effects.

Dependent variable: *GDPpct* change	(1)	(2)	(3)	(4)
log(*distance_east*)	−0.002** (0.001)			
trade_east		0.010 (0.014)	0.048*** (0.015)	
TCostchange		−0.023*** (0.001)	−0.018*** (0.002)	−0.016*** (0.002)
imp				0.005 (0.003)
exp				−0.001 (0.001)
imp_east				0.090*** (0.032)
exp_east				−0.007 (0.031)
unemprate				0.009*** (0.003)
Intercept	0.025*** (0.006)	0.008*** (0.000)		
Observations	213	213	213	213
Country fixed effects	No	No	Yes	Yes
R^2/adjusted R^2	0.027/0.023	0.590/0.586	0.788/0.767	0.798/0.774

Note: Dependent variable is the log of GDP per-capita change. Standard errors are given within parentheses.
Abbreviations: GDP, gross domestic product; pct, per capita.
**$p < 0.05$; ***$p < 0.01$.

show that regions heavily importing from Eastern Europe enjoy an increase in GDP, confirming that it is through cheaper imports that these regions can gain competitiveness and increase production. The coefficient related to exports, in contrast, is not statistically significant at standard levels.

Lastly, the model specification of column (4) also includes the local unemployment rate (*unemprate*) as a control. Its estimated coefficient further illustrates the importance of initial conditions: a higher initial unemployment rate (which amounts to spare capacity in the local economy), on average is associated with a slightly higher GDP change in the nontargeted regions due to the road infrastructure investment in Eastern Europe.

Overall, our analysis suggests that the ECP-related improvements in road transport infrastructure in low-income regions benefit other EU regions, particularly those with more significant trade links with Eastern Europe. The heterogeneity across regions in terms of sectoral composition, and the geography of their trade links, carries over to the results which show heterogeneous economic outcomes between regions, even within the same country.

CONCLUSION

There is no consensus in the economic literature regarding the size and the direction of the effects expected from investments in transport infrastructure on regional and country-level development, especially considering the spillover effects. This paper aims to answer this important research question by combining a detailed transport model with a large-scale general equilibrium model calibrated with data for all the EU NUTS-2 regions. This detailed modeling framework with many regions captures interdependencies through trade and factor mobility, and sectoral disaggregation accounting, for example, for the existence of economies of scale and nontradables.

As a case study, we consider the €30 billion of road transport infrastructure investments implemented in the context of the 2014–2020 ECP, which mainly targets the less developed regions in Eastern Europe. Our results suggest that the decrease in transportation costs generates substantial increases in trade and GDP in the regions targeted by the policy. Positive effects are also recorded in countries such as Finland and Greece, for which road traffic with the economic core passes through the regions where the roads are improved. The size of the effect on GDP is significant, considering that we are abstracting from any demand-side effects of the investments.

We also find positive spillover effects in all the other regions of the EU. They are larger and close to the location of investment. We observe relative winning and losing regions within countries. We analyze the role played by distance, the existence of national borders, and trade flows in shaping the spatial distribution of these spillovers. We find that, within countries, the existence of significant imports from the regions targeted by the policy intervention is associated with positive spillovers, whereas export trade intensity has no significant effect. This suggests that the regions benefitting the most in terms of spillovers do so via cheaper imports, becoming more competitive and increasing their exports to the detriment of other regions. This effect can be seen in regions directly bordering the countries where the investment is taking place, but, perhaps surprisingly, also within countries located quite far from the location of investment, such as France or Spain. These idiosyncrasies in the spillovers are caused by the underlying trade patterns.

Taken together, our results uncover a rich geography in the direct effects and spillovers generated by road transport infrastructure investment. Further research could focus on how our results depend on key modeling assumptions such as the production technology or the structure of the Armington nests of interregional trade. Our work can also offer a guide to future econometric work which could further investigate and validate or falsify the proposed mechanisms in real data, as they become available over time.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Jorge Díaz-Lanchas http://orcid.org/0000-0002-3031-9683
Giovanni Mandras http://orcid.org/0000-0003-1306-0224
Simone Salotti http://orcid.org/0000-0003-1898-6683

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APPENDIX A: THE MODEL

Sets

The model includes 268 regions indexed by $s = 1, \ldots, R + 1$, of which a subset corresponds to $R = 267$ endogenous EU+UK NUTS-2 regions, which we index as $r = 1, \ldots, R$; and one single exogenous region representing the ROW.

The model has a set of different economic sectors (also called industries) indexed by $i \in \boldsymbol{I}$. A subset of these industries indexed by $f \in \boldsymbol{F} \subset \boldsymbol{I}$ operates under monopolistic competition à la Dixit and Stiglitz (1977). In each region sector (r, f), identical firms produce a differentiated variety, which is considered an imperfect substitute for the varieties produced within the same region and elsewhere. The number of varieties in sector F is endogenous and determined from the

TABLE A1 Sectoral classification.

Code NACE rev.2	Sectors description T
A	Agriculture, Forestry and Fishing
B, D, E	Mining and Quarrying+Electricity, Gas, Steam and Air Conditioning Supply+Water Supply; Sewerage, Waste Management and Remediation Activities
C	Manufacturing
F	Construction
G–I	Wholesale and Retail Trade; Repair of Motor Vehicles and Motorcycles+Transportation and Storage+Accommodation and Food Service Activities
J	Information and Communication
K–L	Financial and Insurance Activities/Real Estate Activities
M–N	Professional, Scientific and Technical Activities+Administrative and Support Service Activities
O–Q	Public Administration and Defense; Compulsory Social Security+Education+Human Health and Social Work Activities
R–U	Arts, Entertainment and Recreation+Other Service Activities+Activities of Households as Employers; Undifferentiated Goods- and Services-Producing Activities of Households for Own Use+Activities of Extraterritorial Organizations and Bodies

zero-profit equilibrium condition, according to which profits must be equal to fixed costs. The rest of the firms operate under perfect competition in sectors indexed by $c \in \boldsymbol{C} \subset \boldsymbol{I}$. Currently, the model is disaggregated into 10 NACE rev.2 economic sectors as reported in Table A1: A, B–E, C, F, G–I, J, K–L, M–N, O–Q, and R–U. We assume the following sectors under a perfectly competitive market structure: A, O–Q, and R–U. The rest are normally treated as imperfectly competitive sectors.

Households

Given the consumption of the composite good C_r, the household's problem consists in the maximization of the utility (A1) subject to the budget constraint[7] (A2)

$$U(C_r) = C_r, \tag{A1}$$

$$P_r^c C_r \leq (1 - s_r) YC_r, \tag{A2}$$

where P_r^c, s_r, and YC_r are the consumer price index, the exogenous saving rate, and the disposable income, respectively. YC_r, is specified as the sum of labor and capital income adjusted for taxes and net transfers of income

$$YC_r = \left(1 - \tau_r^w\right) W_r L_r (1 - u_r) + \sum_i \psi_r \left(1 - \tau_r^\pi\right) K_{r,i}^P r k_{r,i} + TR_r, \tag{A3}$$

where ψ_r is the share of capital income paid directly to households and τ_r^w, τ_r^π are the average rate of labor and capital income tax, respectively. W_r and rk_r are the nominal wage rate and the rate of return to capital, respectively. K_r^P is the private capital stock, while L_r and u_r are the total labor force and unemployment rate. TR_r represents net transfers from the government.

[7]For the sake of readability, we omit time indices when describing static equations.

Given Equations (A1) and (A2), the aggregate consumption level is directly related to the disposable income YC_r:

$$C_r = \frac{(1 - s_r)YC_r}{P_r^c}, \tag{A4}$$

where $(1 - s_r)$ is the share of disposable income allocated to consumption. Households consume all varieties of final goods available in the economy

$$C_r = \left(\sum_j N_{r,i}\vartheta_{r,j}(c_{r,j})^{\rho^c}\right)^{\frac{1}{\rho^c}}, \tag{A5}$$

where $c_{r,j}$ is the consumption in region r and sector j. $\vartheta_{r,i}$ is a share of expenditure parameter and $\rho^c = \frac{\sigma^c - 1}{\sigma^c}$, where σ^c is the elasticity of substitution. The consumption price index P_r^c is a CES index defined over the Armington price for each of the varieties, $P_{r,j}$ (this is defined below in Equation A20)

$$P_r^c = \left(\sum_j \vartheta_{r,j}(P_{r,j})^{\rho^c}\right)^{\frac{1}{\rho^c}}. \tag{A6}$$

Saving S_r is determined in fixed share of disposable income

$$S_r = s_r YC_r. \tag{A7}$$

Government

The government deficit (or surplus) is represented in Equation (A8)

$$B_r = \sum_j G_{j,r} + I_r^g + Tr_r - \left(\tau_r^w W_r L_r (1 - u_r) + \psi_r \tau_r^\pi K_r^P r k_r + \sum_j \tau_r^p Z_{r',j} P_{r,j}\right). \tag{A8}$$

Government expenditure includes current spending on goods and services $G_{r,j}$ and net transfers to households TR_r. Revenues are generated by taxes on household income at the rate of τ_r^w and τ_r^π, respectively, and indirect taxes on production $Z_{r,j}$ at the rate of τ_r^p. We assume fixed government consumption and no variations in tax rates. Net transfers to Households are adjusted to reflect changes in prices:

$$Tr_r = \overline{Tr_r} P_r^c. \tag{A9}$$

Firms

At the level of firm, the production technology is represented by a multilevel CES function graphically represented in Figure A1.

In each sector j, and region r, total production $Z_{r,j}$ is a CES combination of the value added $Y_{r,j}$ and intermediate inputs $V_{r,j}$:

$$Z_{r,j} = Ax_{r,j}\left[\delta_{r,j}^x \times V_{r,j}^{\rho_j^x} + \left(1 - \delta_{r,j}^X\right) \times Y_{r,j}^{\rho_j^x}\right]^{\frac{1}{\rho_j^x}}, \tag{A10}$$

where $\delta_{r,j}^x$ is the calibrated share of intermediate inputs in sector j for region r in total production, while $Ax_{r,j}$ is a scale parameter and ρ_j^x is the elasticity parameter obtained from the elasticity of substitution σ^x, according to

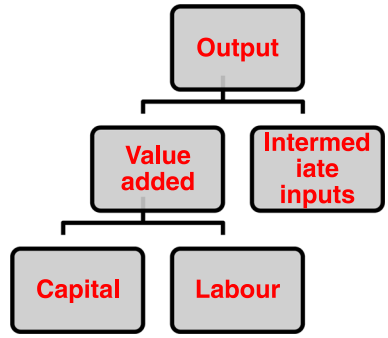

FIGURE A1 Hierarchical production structure.

$\rho_j^x = \frac{\sigma^x - 1}{\sigma^x}$. The corresponding demand equations for *Y* and V are described below in Equations (A11) and (A12), respectively, as

$$Y_{r,j} = \left(Ax_{r,j}^{\rho_j^x} \times (1 - \delta_{r,j}^x) \times \frac{Py_{r,j}}{Pz_{r,j}}\right)^{\frac{1}{1-\rho_j^x}} \times Z_{r,j}, \tag{A11}$$

$$V_{r,j} = \left(Ax_{r,j}^{\rho_j^x} \times \delta_{r,j}^x \times \frac{PIN_{r,j}}{Pz_{r,j}}\right)^{\frac{1}{1-\rho_j^x}} \times Z_{r,j}, \tag{A12}$$

where $Pz_{r,j}$, $Py_{r,j}$, and $PIN_{r,j}$ are the prices for the total production, the value added and the intermediate inputs, respectively.

$Y_{r,j}$ and $V_{r,j}$ are defined as follows in Equations (A13) and (A14), respectively:

$$Y_{r,j} = Ay_{r,j}\left[\left[\delta_{r,j}^Y \times KD_{r,j}^{\rho_j^y} + \left(1 - \delta_{r,j}^y\right) \times LD_{r,j}^{\rho_j^y}\right]^{\frac{1}{\rho_j^Y}}\right] - FC_{r,j}, \tag{A13}$$

$$V_{r,j} = \left(\sum_i b_{r,i,j} v_{r,i,j}^{\rho^v}\right)^{\frac{1}{\rho^v}}. \tag{A14}$$

$Y_{r,j}$, is CES combination of private capital $KD_{r,j}$ and employment $LD_{r,j}$ net of fixed costs $FC_{r,j}$. $Ay_{r,j}$ is the scale parameter and δ_j^y is the share parameter of capital. Substitution between the two types of primary factors is governed by the parameter of substitution $\rho_j^y = \frac{\sigma^y - 1}{\sigma^y}$ (where σ^y is the elasticity of substitution between labor and capital) and the share parameter.

The input–output relations are shown in Equation (A14), where $v_{r,i,j}$ is the purchase of intermediate inputs of each sector *j* from the supplier sector *i*. Input substitution between sectors is determined by the elasticity of substitution $\rho^v = \frac{\sigma^v - 1}{\sigma^v}$ given the share of expenditure $b_{r,i,j}$.

The composite CES price index for the intermediate inputs is determined as follows:

$$PIN_{r,j}^{1-\sigma^v} = \sum_i b_{r,i,j} p_{r,i}^{1-\sigma^v}. \tag{A15}$$

The production price is then defined as

$$Pz_{r,i} Z_{r,i} = Py_{r,i} Y_{r,i} + PIN_{r,i} V_{r,i}. \tag{A16}$$

Given Equation (A13), the demand for capital and labor in each sector j is represented in Equations (A17) and (A18), respectively, as

$$KD_{r,j} = \left(\left(\left(K^{d}_{(g)}\right)^{\xi} Ay_{r,j}\right)^{\rho^{y}_{j}} \delta^{y}_{r,j} \frac{rk_{r,j}}{Py_{r,j}}\right)^{\frac{1}{1-\rho^{y}_{j}}} Y_{r,j}, \tag{A17}$$

$$LD_{r,j} = \left(\left(\left(K^{d}_{(g)}\right)^{\xi} Ay_{r,j}\right)^{\rho^{y}_{j}} \left(1 - \delta^{y}_{r,j}\right) \frac{W_r}{Py_{r,j}}\right)^{\frac{1}{1-\rho^{y}_{j}}} Y_{r,j}, \tag{A18}$$

where $rk_{r,j}$ and W_r are, respectively, the price of capital and the wage rate. For each firm, labor is then further disaggregated.

Trade

At the level of firm, the demand for each good and services, j, supplied by region s to region s', $x_{r,'j}$, is defined as follows:

$$x_{s,s',j} N_{s,j} = \eta_{s,s',j} \left(\frac{P_{s',j}}{p_{s,s',j}}\right)^{\sigma_j} X_{s,j}, \quad \sigma_j \geq 0, \tag{A19}$$

where $\eta_{s,s',j}$ is a calibrated expenditure share, σ_j is the elasticity of substitution, and $X_{s,i}$ is the Armington aggregate of outputs defined below in Equation (A30). Having external prices fixed to one (such as import prices from the ROW), the price $P_{r',j}$ is defined as a CES price index over the market price $p_{r,r',j}$:

$$P^{1-\sigma_j}_{r,j} = \sum_{s} \left[\eta_{s,r,j} N_{s,j} p^{1-\sigma_j}_{s,r,j}\right] r \subset s, \tag{A20}$$

where the price $p_{r,r',j}$ set by a firm of region r (net of transport cost τ and production taxes τ^{p}_{r}) selling to region r', for a monopolistic competitive sectors f, is defined as the optimal mark-up $\left(\frac{\sigma_{r,f}}{\sigma_{r,f}-1}\right)$ over the marginal cost $P^{*}_{r,f}$, is given as follows:

$$p_{r,s,f} = \left(\frac{\sigma_{r,f}}{\sigma_{r,f} - 1}\right)(1 + \tau_{s,r,j})(1 + \tau^{p}_{s}) P^{*}_{r,f}. \tag{A21}$$

The elasticities of substitution and markups are equal for all firms and products in the monopolistic sectors of the model. For the perfectly competitive sectors, the market price is equal to the marginal cost, that is:

$$p_{r,s,c} = P^{*}_{r,c}, \quad c \in i. \tag{A22}$$

The marginal cost includes the cost of production factors and the intermediate price index as follows:

$$P^{*}_{r,j} = a^{y}_{r,j} Py_{r,j} + a^{Int}_{r,j} PIN_{r,j}, \tag{A22}$$

where $a^{y}_{r,j}$ and $a^{Int}_{r,j}$ are the share parameters attached to the value-added and intermediate inputs, respectively.

Wage setting

The model incorporates a wage curve according to which the real wage $\boldsymbol{rw_t}$ is negatively related to the unemployment rate, $\boldsymbol{u_t}$. $\boldsymbol{\beta}$ is the elasticity parameters obtained from previous studies and a is a constant

$$rw_{r,t} = a - \beta u_{r,t}. \tag{A24}$$

Investment

The optimal path of private IP investments is consistent with the neoclassical firm's profit maximization theory and defined as in Uzawa (1969)

$$I^P_{i,r} = \delta_r K^P_{i,r}\left(\frac{rk_{i,r}}{uck_r}\right)^v, \tag{A25}$$

where v is the accelerator parameter and δ is the depreciation rate. According to this formulation, the investment capital ratio ($\varphi = I^P_r/K^P_r$) is a function of the rate of return to capital (rk) and the user cost of capital (uck), allowing the capital stock to reach its desired level in a smooth fashion over time.

The user cost of capital, uck, is derived from Hall and Jorgenson (1967) and Jorgenson (1963) as a typical no-arbitrage condition, where

$$uck_r = (r + \delta_r)p^I_{\text{EU}} + \Delta p^I_{\text{EU}} + rp_r, \tag{A26}$$

r, δ_r, p^I_{EU}, and rp_r denote the interest rate, the depreciation rates, the investment price index at EU level, and an exogenous risk premium respectively. Δp^I_{EU} is the change of the investment price index defined between two subsequent periods.

In Equation (A27), the interest rate is fixed and equal for all regions; δ_r is the depreciation rate; rp_r is a fixed calibrated parameter obtained as residual. p^I_{EU} is given as the price index over the Armington price weighted by the capital matrix KM:

$$p^I_{\text{EU}} = \frac{\sum_{i,j,r} KM_{i,j,r}P_{r,i}}{\sum_{i,j,r} KM_{i,j,r}\bar{P}_{r,i}}. \tag{A27}$$

Private capital stock in each region updates period by period through investments adjusted by depreciation

$$K^P_{r,t+1} = (1 - \delta_r)K^P_{r,t} + I^p_{r,t}. \tag{A28}$$

The demand for investments $I^P_{j,r}$ in sector j is translated to the production of investment goods produced by sector i, $I^S_{j,r}$, through the capital matrixes $KM_{i,j,r}$ as follows:

$$I^S_{i,r} = \sum_j KM_{i,j,r}I^P_{j,r}. \tag{A29}$$

Commodity balance and closing the system

Equilibrium in the commodity market is defined as follows in Equation (A30):

$$X_{r',i} = \sum_j N_{r,i}v_{r,i,j} + N_{r,i}c_{r,i} + I^S_{i,r} + G_{r,j} + I^{gS}_{i,r}. \tag{A30}$$

Capital demand equals the capital stock

$$N_{r,j}KD_{r,j} = K^P_{r,j}. \tag{A31}$$

The labor market is equilibrated

$$\sum_j N_{r,j}LD_{r,j} = (1 - u_r)L_r, \tag{A32}$$

where labor supply L_r evolve according to interregional migration. We only consider migration between EU and UK NUTS-2 regions; therefore, population remains fixed considering the EU and the United Kingdom as a whole. The number of people migrating from region r to region r' in a given time period t is $L_{r,t}z_{r,r',t}$, with $s_{r,r',t}$ the share of these individuals that choose to move to r' over the time period. The set of possible destinations includes the origin region itself, and therefore $\sum_{r'} s_{r,r',t} = 1$. The change in the number of individuals in r is given by the difference between the sum of immigration from all origins, and total outward migration considering all destinations

$$L_{r,t+1} - L_{r,t} = \sum_{\substack{r' \\ r' \neq r}} L_{r',t} z_{r',r,t} - \sum_{\substack{r' \\ r' \neq r}} L_{r,t} z_{r,r',t}. \tag{A33}$$

The migration shares s are estimated empirically using a discrete choice framework, with regional income, unemployment, the geodesic distance between the regional geographic centers, and international border dummies as explanatory variables (see Brandsma et al., 2014): write $E[l_{r'}] = W_{r'}(1 - u_{r'})/P^c_{r'}$ for the expected real labor income in each potential location r'. Migrants ignore regional differences in transfers and capital rents in their decision. Migration costs depend both on the geographic distance $distance_{r,r'}$ and the presence of international borders indicated by $I(border_{r,r'})$. More formally, each individual household i currently living in region r chooses the region r' that maximizes $U^M_{r,r'i}$

$$U^M_{r,r'i} = V^M_{r,r'} + \varepsilon^M_{r,r',i} = \beta_{0r'} + \beta_1 \log(pop_{r'}) + \beta_2 \log(E[l_{r'}]) + \beta_3 \log(distance_{r,r'}) + \beta_4 I(border_{r,r'}) + \varepsilon^M_{r,r',i},$$

where the $\beta_{0r'}$ are region-specific terms and the $\varepsilon^M_{r,r',i}$ terms are iid extreme value distributed with scale parameter σ^M. The utility of choosing a region is assumed to increase with its size, which we proxy here by its population. This can be derived formally in a framework where individuals can take a number of draws in the destination which is proportional to its size (proxied by the population) as in Kennan and Walker (2011), or can freely choose from a number of alternatives within destinations as in Kanaroglou and Ferguson (1996), McFadden (1977), or Persyn (2021), with this number proxied here by the regions' population.

Under these assumptions, as shown by McFadden (1974), the probability of migration from r to r' takes the familiar logit form. Moreover, if the number of individual households in each region is large this probability equals the share $s_{r,r'} = m_{r,r'}/pop_{r,r'}$ of households from r that migrate to r', such that

$$s_{r,r'} = \frac{\exp\left(V^M_{r,r'}/\sigma^M\right)}{\sum_{r'} V^M_{r,r'}/\sigma^M}.$$

These expressions show that under appropriate assumptions the random utility framework leads to aggregate migration behavior that is described by a logit model, which can be equally seen as a gravity model (bringing $pop_{r'}$ to the right, see Anas, 1983) or a CES demand system (see Anderson et al., 1987).

Expected income differences and migration costs affect migration flows, but only to the degree by which these variables affect the observed part of utility V relative to the dispersion in the idiosyncratic components. If individuals have widely varying unobserved preferences over regions, then even large income differentials will lead to few people migrating, and migration then does not lead to equalization of the observed part of utility (such as expected income) between regions (see also Behrens & Murata, 2021). This microfoundation of the migration behavior offers a consistent framework both for the CGE model and for the econometric estimation of the parameters. The values for the various β/σ parameters are taken from Brandsma et al. (2014) who estimate this model considering the log odds of the above expression, using yearly Eurostat data on intraregional migration flows at the NUTS-2 level. Following these authors, we allow for heterogeneity in the parameter β_2/σ^M between the own region and other destinations to capture additional ties to the home region, that would make individuals less sensitive to changes in the expected income in the current residence; the parameters are shown in Table A2.

TABLE A2 Parameters reproduced from Brandsma et al. (2014) determining migration behavior.

Associated variable	Parameter	Value
$\log(pop_{r'})$	β_1/σ^M	0.52
$\log(E[I_{r'=r}])$	$\beta_{2,r'=r}/\sigma^M$	0.99
$\log(E[I_{r'=r}])$	$\beta_{2,r'=r}/\sigma^M$	0.67
$\log(distance_{r,r'})$	β_3/σ^M	−0.76
$I(border_{r,r'})$	β_4/σ^M	−4.22

The region-specific factors $\beta_{0r'}/\sigma^M$ are calculated numerically using the model to ensure zero net migration in every region in the baseline.

The zero profit condition that links output price and average price determines the number of firms in the system for the f sectors

$$FC_{r,f}P^*_{r,f}N_{r,f} = \sum_{r'} N_{r,f}x_{r,r',f}p_{r,r',f} - P^*_{r,f}N_{r,f}(Y_{r,f} + V_{r,f}). \tag{A34}$$

Furthermore, the regional output should be equal to the overall goods and services traded domestically and outside the region

$$Pz_{r,i}Z_{r,i} = \sum_{s'} x_{r,s',i}p_{r,s',i}\left(1 + \tau^p_{i,r}\right). \tag{A35}$$

Definition of equilibrium: Given initial factors' endowment $\overline{L}_r, \overline{K}^p_{i,}$, the equilibrium of the economy is determined for each region r and each sector i, as a set of consumers' decision {C,S}, investors' decisions (I^p), firms' decision {Z, Y, V, v, N, KD, LD, X, x} that along with price formation {P^c, P^I, P^*, Pz, Py, Pin, P, p, rk, W, w, uck}, all markets clear (goods and service market, labor and capital market, payment account), and satisfy the low of motion for private capital and the labor market conditions through the unemployment rates for each region and sectors.

The configuration of the model ensures an unconstrained inflow of capital to sustain investment whenever required (this is a typical regional macroeconomic closure), not imposing any constraints on the balance of payments. Typically, no binding constraints are imposed on regional government balance. However, foreign savings from the ROW in the model are passive, hence maintaining equilibrium in the payment accounts with the ROW.

The high dimensionality of the model in terms of regions and sectors implies that the number of (nonlinear) equations to be solved simultaneously is very large (in the order of hundreds of thousands). Therefore, to keep the model manageable from a computation point of view, its dynamics are kept relatively simple. The model is solved in a recursively dynamic mode, where a sequence of static equilibria is linked to each other through the law of motion of state variables. This implies that economic agents are not forward-looking and their decisions are solely based on current and past information.

APPENDIX B: DATA, CALIBRATION, AND ELASTICITIES

The model calibration process assumes the regional economies to be initially in steady-state equilibrium. All shift and share parameters are calibrated to reproduce the base year (2013) data in the EU interregional SAM derived from Thissen et al. (2019). The number of firms in each region and sector is derived from the European Structural Business Statistics (Eurostat, 2017), while fixed costs are computed using the equilibrium condition in Equation (A35) and subsequently added to production.

TABLE B1 Selected calibrated shares.

	Average across regions	Standard deviation
Export total/GDP	0.78	0.79
Export to ROW/GDP	0.15	0.17
Import total/GDP	0.82	0.25
Import from ROW/GDP	0.11	0.09
Labor income shares	0.58	0.10
Share value added in total production	0.39	0.08
Investment/GDP	0.19	0.07
Consumption/GDP	0.83	0.17
Iceberg transport costs (average)	0.33	0.23

Abbreviations: GDP, gross domestic product; ROW, rest of the World.

TABLE B2 Elasticity parameters.

σ^c	0.3
σ^x	0.3
σ^y	0.4
σ^v	0.2
σ_j	4
α	0 (default case) or 0.1 under dynamic adjustment over wage bargaining
β	0.1
ς	0 (default case) or 0.25 under dynamic adjustment over wage bargaining
θ	0 (default case) or 0.03 under dynamic adjustment over wage bargaining
v	1
ir	0.15 (annual interest rate)
δ_r	0.15

For illustrative purposes, regional average, and associated standard deviation of selected calibrated share parameters are reported in Table B1. The structural and behavioral parameters of the model are either borrowed from the literature or estimated econometrically. These are summarized in Table B2 and discussed further in this section.

The interest rate is set to 0.04, and the rate of depreciation is set to 0.15. The risk premium is a calibrated parameter and is determined as a residual from Equation (A27).

The parameters related to the elasticities of substitution both on the consumer and on the producer sides are based on similar models or derived from the econometric literature.

For the capital-labor substitution elasticity, the literature provides a wide range of estimates and there is a strong evidence in support of elasticity lower than 1[8] (Chirinko, 2008; Chirinko et al., 2011; Kemfert, 1998; Koesler & Schymura, 2015; Krusell et al., 2000; León-Ledesma et al., 2011; Okagawa & Ban, 2008; Van der Werf, 2008). In light of this empirical evidence, we fairly set this elasticity equal to 0.4.

Existing studies on the estimation of Armington trade elasticities display substantial variations. Our default Armington elasticity is set equal to 4.[9]

As for the wage curve parameterization, we typically run a long-run wage curve assuming $\beta = 0.1$[10] (Nijkamp & Poot, 2005).

The speed of adjustment in the model is captured by the elasticity of the cost of capital v. In our default simulations, this parameter takes the value of 1 as in Uzawa (1969). Estimates of the elasticity of the capital costs can vary widely; for instance, in Caballero et al. (1995), it can take a value in the range of 0.01–2, while in the study of Caballero and Engel (2003), it is in the range of 0.2–2.5.

APPENDIX C: TRANSPORT DATA DESCRIPTION AND FURTHER RESULTS

(Figures C1 and C2 and Table C1)

The subset of the OSM road network used in the analysis contains motorways, trunk roads, primary roads, secondary roads, and ferry lines for a total length of about 1,500,000 km over a surface area of about 5,730,000 km², giving an average road density of 0.26 km/km^2.

Regression explaining the regional changes in GDP

The coefficients associated with two measures of trade openness (relexp and relimp) and the initial level of unemployment are not statistically significant at standard levels, but the interaction term between the latter and the change in transport cost reveals interesting findings. For a region with an unemployment rate close to 0%, a decrease in the average transport cost by 3.5% (this is a typical value in the most affected regions) would lead to a 0.1% higher GDP (-3.5×-0.028), all else equal. Regions with higher unemployment rates, though, would benefit more: for an unemployment rate of 10%, the effect of a similar decrease in transport costs would be almost twice as large, at 0.18% ($((-3.5 \times -0.028) + 10 \times (-0.00242) \times (-3.5))$). Note that in regressions we express variables corresponding to changes as percentages, that is, a value of 1 implies an increase of 1%.

[8]See Acemoglu (2003).

[9]Estimates diverge for the level of aggregation, the estimation techniques or whether time series or cross-sectional data are used. This value finds justification from econometric estimates obtained using a European data set derived from the work of Aspalter (2016), Németh et al. (2011), and Olekseyuk and Schürenberg-Frosch (2016), where elasticities range from around 2 to 5, in the interval of 3–4.2 and 0.3–3.7, respectively. These elasticities appear to be consistent with other studies where single European countries are considered (Imbs and Méjean, 2010, 2015; Welsch, 2008). However, elasticities might be different across industries and across countries. Variation between "microelasticities" and "macroelasticities" could be significant (typically the former lower than the latter). This is for example the case of the United States (Feenstra et al., 2014; Imbs & Mejean, 2015) and to a less extent in Europe, as shown in Aspalter (2016); therefore, sensitivity analysis around the trade elasticities is of utmost importance to deliver a range of results to the policy makers that are not biased in one direction.

[10]Most of the studies on the relationship between unemployment and wages find an elasticity close to −0.1 as summarized by the meta-analysis carried out by Nijkamp and Poot (2005). This confirms the original studies of Blanchflower and Oswald (1994).

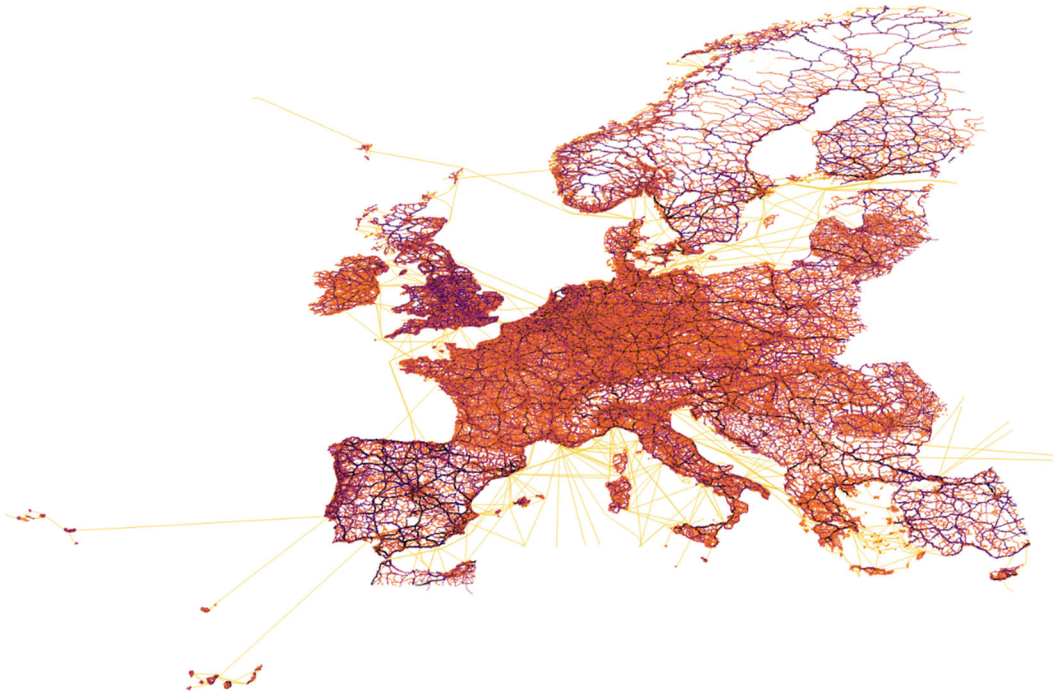

FIGURE C1 Road and ferries networks (2017) were included in the analysis. *Source*: OpenStreetMap.

FIGURE C2 Selected regions for the analysis of spillovers and the ripple effect.

TABLE C1 Cross-sectional estimates on the long-run GDP per capita (deviation from base year value).

Predictors	GDP_Expend_50cap Estimates
(Intercept)	0.004 (0.005)
pcttranscostchange	−0.028*** (0.004)
unemprate	0.000 (0.000)
relexp	−0.002 (0.006)
relimp	0.018 (0.015)
pcttranscostchange × *unemprate*	−0.002*** (0.001)
Observations	267
R^2/R^2 *adjusted*	0.745/0.740

***$p < 0.01$.