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# The ripple effects of large-scale transport infrastructure investment

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**Abstract**. We analyse 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 in the context of the EU cohesion policy programme. Our analysis suggests that the decrease in transportation costs benefits the regions targeted by the policy via substantial increases in GDP and exports compared to the baseline, and small increases in population. The geographic information embedded in the transport model leads to relatively large predicted benefits in peripheral countries such as Greece and Finland who hardly receive funds, but whose trade links cross Central and Eastern Europe and thus profit from the investments there. The richer, Western European non-targeted 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 spillovers of the policy. In non-targeted countries, 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 neighbouring regions across an international border. Using regression analysis we uncover that regions which import intermediate inputs from Central and Eastern Europe enjoy the largest spillovers. These regions become more competitive and expand exports locally, at the detriment of other regions in the same country.

**JEL Codes**: C68, R11, R13, R15, R41

**Keywords**: transport infrastructure; economic geography; computable general equilibrium modelling

## Executive summary

Countries dedicate significant resources to transport infrastructure construction and maintenance. Vast investment projects are grounded on the expected positive returns of transport infrastructure on economic performance. It is therefore surprising that there is no consensus among economists on the size or even the direction of the effects to be expected from such investments on development at the regional and country level. Puga (2002), for example, emphasises 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 affect the complex mutually dependent location choices of workers and firms in unintended ways.

The findings of Duranton (2015a and 2015b) on agglomeration effects in urban areas also suggest that transport infrastructure may affect development and trade in ways which are difficult to predict. Empirical ex-post analyses remain unclear on the expected economic impact of transport infrastructure investment projects. Most studies find inconclusive results which make it hard to settle the dispute on whether the periphery or the core benefit from the construction of large transport infrastructures (see, among others, Faber, 2014; and Ahlfeldt and Feddersen, 2018).

In this paper, we contribute to this literature by combining a detailed transport model with a large scale spatial dynamic computable general equilibrium (CGE) model calibrated on a system of Social Accounting Matrices (SAMs) for all the NUTS 2 regions of the EU and with a fine level of granularity in terms of, among other things, economic sectors and factors of production. Many of the model components are highly relevant to determine the location of economic activities, such as the mobility of both labour and capital, the existence of increasing returns to scale in the sectoral production functions, and on the trade flows of intermediate inputs used for production.

Our transport model relies on estimating a generalised transport cost measure (Zofío, et al., 2014; Persyn, et al., 2020) for the NUTS 2 regions of the EU, considering a variety of components of road transports costs such as fuel costs and wages. Taking into account these components the transport costs are calculated as the minimum cost route for a truck to move across a digitised European road network containing more than 4 million road segments, taking into account road type and geography. The transport model also allows to consider different counterfactual transport cost-scenarios whose economic impacts can be assessed with the CGE model.

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

The case study we use to answer the above research questions is 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 European Union (EU). The stated goal of this policy is to achieve economic and social cohesion by reducing disparities between EU regions, thus promoting more balanced and sustainable territorial development. Our analysis verifies whether the large-scale road infrastructure investments contribute to this goal. Some key questions we want to answer in this paper are the following: (i) do the lower transport costs lead to a shift of economic activity to the periphery, which is receiving the funds, or rather 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 the spillovers?

Our analysis suggests that the decreases in transportation costs generate substantial increases in the trade and GDP 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, but rather solely concentrate on the structural supply-side impact stemming from the decrease in transportation costs associated with the infrastructure investments. Finally, we highlight the existence of and spatial structure of spillover effects. We find economic benefits in all the regions of the EU, including those in which ECP funds are not spent. We uncover the role played by distance, the national borders, and trading flows in shaping the distribution of the spillovers. We find that spillovers are not homogeneously decaying with distance, but rather exhibit ripples: on average within each country, regions with stronger trade ties to Eastern Europe (often but not always these are regions closer to the location of investment in Eastern Europe and Poland in particular), are benefitting more compared to other regions within the same country. Using regression analysis, we uncover that regions with strong backward linkages to Central and Eastern Europe benefit relatively more from spillovers from the road transport infrastructure investment.

# 1 Introduction

Countries dedicate significant resources to transport infrastructure construction and maintenance. Vast investment projects are grounded on the expected positive returns of transport infrastructure on economic performance. It is therefore surprising that there is no consensus among economists on the size or even the direction of the effects to be expected from such investments on development at the regional and country level. Puga (2002), for example, emphasises 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 affect the complex mutually dependent location choices of workers and firms in unintended ways. Many channels operate simultaneously and depend both 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. The findings of Duranton (2015a and 2015b) on agglomeration effects in urban areas also suggest that transport infrastructure may affect development and trade in ways which are difficult to predict.

Empirical ex-post analyses remain unclear on the expected economic impact of transport infrastructure investment projects. Most studies find inconclusive results which make it hard to settle the dispute on whether the periphery or the core benefit from the construction of large transport infrastructures (see, among others, Faber, 2014; and Ahlfeldt and Feddersen, 2018).

Early economic models considering the economic effects of lower transport costs, both numerical and analytical, 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; Krugman, 1993; Fujita, et al., 1999; Ago, et al., 2006; Barbero and Zofío, 2016). More recent contributions span from empirical ex-post assessments of transport infrastructure investments (Duranton, et al., 2014; Koster, et al., 2021) to multi-region models that are much more ambitious in scale and complexity (Redding and Turner, 2015; Allen and Arkolakis, 2021; Fajgelbaum and Schaal, 2020; Hayakawa, et al., 2021). 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 computable general equilibrium (CGE) model calibrated on a unique dataset available for all 267 EU and UK NUTS2 regions that fully account for bilateral trade in final and intermediate goods from 10 economic sectors. Many of the model components are highly relevant to determine the location of economic activities, such as the mobility of both labour and capital, the existence of increasing returns to scale in the sectoral production functions, and the trade in intermediate inputs used for production.

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The remainder of the paper is organised as follows. Section 2 reviews the literature on the economic assessment of transport infrastructure. Section 3 briefly explains the main features of the modelling framework with a focus on transport costs. Section 4 illustrates the application of the transport model to the road transport infrastructures investments of the ECP, and section 5 contains the results of the simulations carried out with the CGE model. Finally, Section 6 concludes.

## 2 Literature Review

A large body of literature has studied how transport cost and investments in transport infrastructure affects the location of economic activity and economic outcomes (see Redding and Turner, 2015, for an in-depth review). The main tools to estimate the effects of transport infrastructure investments are econometric analyses and economic models.

Multiple econometric estimates, covering different geographic areas, have found that the effect of transport infrastructure on economic output is positive and stronger in the long-run than in the short-run (for a meta-analysis, see Melo et al., 2013). Duranton, et al. (2014) study the broad case of the US highway system and its historical impacts on US cities as well as on their trade performance. These authors find that highways affect the industry and employment compositions of cities. Behrens et al. (2018), using plant-level data and ad valorem transport costs for Canadian manufacturing industries between 1992 and 2008, find that small changes in transport costs affect the geography of industries even when transport costs are already low.

Beyond impacting the region where the infrastructure is built, road transport infrastructure generates important spillover effects. Most empirical studies resort to macro-economic production functions and quasi-experiments to quantify these effects. Arbués et al. (2015) incorporate transport infrastructure in a production function and, using spatial econometric techniques, find that road infrastructure positively affects other provinces' productivity in Spain. Álvarez et al. (2016) extend the production function to incorporate internal and imported transport capital stock – measured as the monetary value of roads and highways located in other regions that trucks use to trade goods. They find that there are significant spillover effects derived from the road network capital stock both in neighbouring areas and in non-adjacent locations. Konno et al. (2021) perform a global study using satellite data covering 178 countries and find evidence of positive spatial spillover effects and negative direct impact of road infrastructure investments. However, the study is limited to a cross-section in 2010, thus ignoring possible long-run effects, and assumes that the production technology is the same in different geographic areas of the world. For the case of Europe, Adler et al. (2020), using a harmonised road network for the 28 European countries between 1990 and 2012 and using 19th century market access as an instrument, find that an increase in market access by 1% increases GDP in a region by 0.2%, on average, and employment by 0.7%.

Focusing on quasi-natural experiments to exploit exogenous variation induced by transport infrastructure, Faber (2014) analyses the China's National Trunk Highway System linking provincial capitals with cities above 500,000 inhabitants and finds reductions in GDP growth among non-targeted peripheral counties. This result seems to depend on the trade effect induced by the reduction of inter-regional transport costs. Ahlfeldt and Feddersen (2018) consider the high-speed rail investment project connecting the two German core regions of Cologne and Frankfurt. Ahlfeldt and Feddersen therefore focus on `accidentally' connected locations along this railway to infer the causal effect on GDP. Contrary to the trade channel-operating mechanism, Ahlfeldt and Feddersen (2018) emphasize the positive role of knowledge diffusion and Marshallian economies in shaping spatial spillover effects. Other empirical work that has been developed in parallel to our work include for example Banerjee et al. (2020) and Baum-Snow et al. (2020) who study the impact of highway construction in China using different instrumental variable methods to control for endogeneity.

Beyond econometric studies, the effect of transport infrastructure on economic outcomes such as GDP and welfare has been considered in economic models. As in the majority 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.

A 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 (see for example Laird and Venables, 2017 and De Palma et al., 2011 for an overview). Our aim is to consider large scale infrastructure projects, however, where these general equilibrium effects would play a role, through changes in wages and the return to capital, the relocation of capital and labour between regions, or changing spatial patterns of specialisation, trade flows and consumption.

A second strand utilises new economic geography models à la Krugman (1993) to explain how the interaction of increasing returns to scale and transport costs shapes the spatial allocation of the economic activity. Some notable examples include the works by Fujita et al. (1999), Ago et al. (2006), Barbero and Zofío (2016), and Barbero et al. (2018). With the exception of 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 spatial quantitative models) such as those of Allen and Arkolakis (2014, 2021), Fajgelbaum and Schaal (2020), or Hayakawa et al. (2021).

These spatial quantitative models often consider urban phenomena such as commuting or congestion, which is missing from our model which rather focusses on effects operating through interregional trade in goods and factor mobility over large distances. Relative to this literature our model contributes by considering many sectors and trade in intermediate inputs, thus allowing for `traditional' effects such as increased regional sectoral specialisation in response to a decrease in transport costs, in parallel with the effects operating through economies of scale. By analysing transport separately from the general equilibrium model, our approach allows for a richer modelling of transport costs compared to the fully analytic spatial quantitative models. We model transport costs at the sectoral level, considering estimated costs of shipping goods using a 40 ton truck, taking into account weight and volume, and properties of individual road segments. Separating the transport model from the CGE comes at the cost of excluding general equilibrium effects such as changes in wages to affect the transport costs. Whereas our framework in principle would allow to iterate between the transport and CGE model to endogenise transport costs, we believe these second-round general equilibrium effects would be quite small.

A third strand of literature is the analysis of transport infrastructure investments through large scale CGE models, which have traditionally emphasised disaggregation along multiple dimensions which are often lost in the models discussed before, such as distinguishing between multiple sectors of production, different types of capital and labour, and detailed production structures with intermediate inputs. Examples of this approach can be found in Haddad et al. (2011); Bröcker et al. (2010) 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 CGE models. Compared to this CGE literature, our modelling of transportation is more detailed, however.

Our contribution consists in combining insights from these three model-based approaches. While being decidedly less `analytic', creating a soft-link between the CGE model and a transport model allows to work with a detailed large scale spatial dynamic general equilibrium model, while at the same time taking advantage of a dedicated transport model using information on road networks and a detailed and comprehensive measure of transport costs. This combined detail in both the modelling of transport and in the general equilibrium model is unique and missing in existing models. The detailed approach allows us to obtain realistic estimates of the local impact, while revealing interesting patterns in spillovers to other regions, depending on geography and trade in intermediary inputs (backward linkages).

# 3 The modelling framework

## 3.1 The CGE model

We use a large spatial dynamic CGE model calibrated on a fully integrated system of SAMs for the 267 NUTS 2 regions of the EU, plus a residual region accounting for the rest of the World. In Annex A, we report the full model description of the spatial CGE model. All the regional economies are disaggregated into ten NACE 2 sectors whose nested production structure considers three types of labour (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 inter-regional trade flows using non-linear programming techniques based on information on freight and passenger transport trips. The model has involuntary unemployment modelled 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 CGE model contains mobile production factors. The responsiveness of migration to economic conditions is calibrated using EU intra-regional 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 from the gap between the rate of return to capital and the replacement cost of capital (Uzawa, 1968). This rule ensures that all regions converge to the same rate of return to capital in the long-run. Selected sectors are characterised 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 CES function with love for variety across goods from different regions. Governments intervene in the economy with current expenditure, investment, transfers to households, all financed via tax collection. Firms produce goods and services with a CES production function combining capital and labour, and intermediate inputs domestically produced or imported.

Given that the focus of the analysis is 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 individual EU regions, including the region itself, and the ROW. We use a relatively high Armington elasticity, $\sigma$, of 4 to reflect the fact 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

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

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

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

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

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

The mark-up does not depend on the market shares or 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.

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

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

$a^y_{r,j}$ and $a^{Int}_{r,j}$ 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 realise that the changes in transport costs and product prices will affect many other parts of the general equilibrium model. The adopted framework permits to study these general equilibrium effects of transport infrastructure investments. If a region faces lower transport costs, it will be able to 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 labour demand, higher wages, immigration and investment, higher local income and demand, etc. There will be endogenous adjustments in the spatial distribution of upstream and downstream firms through investment, and of population through migration. All these mechanisms will be captured by the general equilibrium model.

## 3.2 The 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 regionalised by Thissen, et al. (2019). These parameters reflect the structure of inter-regional 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.[1] We first regress a basic log-linear gravity equation for exports from all Western European regions to all Eastern European regions. The results are reported in the left panel of Figure 1. They show a high R-square (0.765), and highly significant coefficients on both distance (the larger the distance between the two regions, the lower the trade volumes) and on regional value added in origin and destination (the larger the value added in either region, the higher the trade volumes between the two regions). Including origin and destination fixed effects lowers the distance coefficient from -0.87 to -0.62.

The right panel of 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. The majority, but not all, of the highest values of the distribution (up to 7.4% of GDP) are recorded for regions which are geographically close to the Eastern European regions.

| | **log(exports)** |
|---|---|
| *Predictors* | *Estimates* |
| distance_road [log] | -0.870 *** (0.022) |
| start_gva [log] | 0.595 *** (0.011) |
| end_gva [log] | 0.870 *** (0.016) |
| Observations | 11084 |
| $R^2$ adjusted | 0.765 |

*Note: * p<0.1 ** p<0.05 *** p<0.01*

*Standard errors in parentheses*

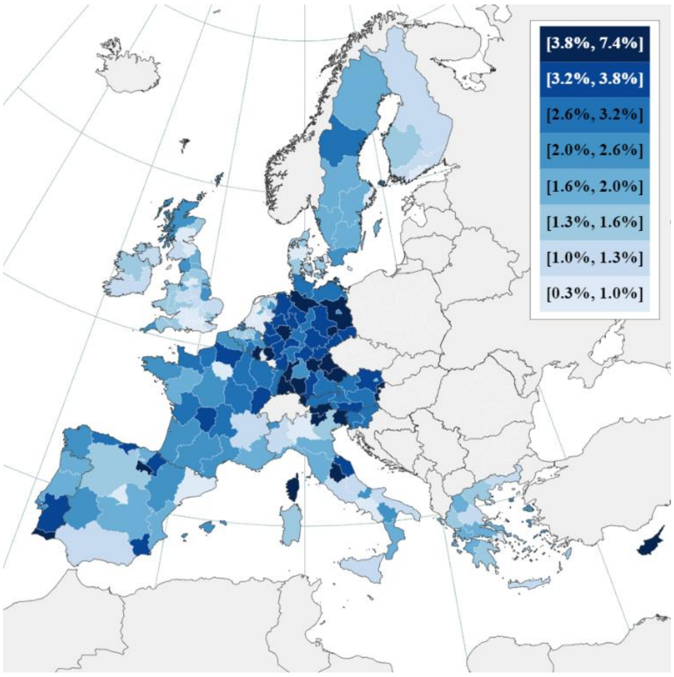


**Figure 1 Regional trade intensity with selected central and eastern European countries**

The map reveals that the simple regression results hide a large amount of residual variation in the relationship between trade intensity and distance. Although on average the trade intensity decreases as the distance to Eastern Europe increases, a surprising amount variation can be seen in the map of regional trade intensities. Many regions that are

[1] 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 example Greece is clearly one of the most eastwardly located EU members.

relatively remote from Eastern Europe have a higher trade intensity than regions that are closer to it. These regional differences at times are due to the presence of a single specialised plant, or specific regional sectoral specialisation or trade link.

## 3.3 Baseline transport costs

For the calibration of the iceberg transport costs $\tau_{r,r',j}$ in equation (3), we use the methodology described in Persyn et al. (2020). We start by taking large samples of centroids from a 1km$^2$ resolution population grid. We define the generalised transport cost (GTC) as the lowest-cost of the trip of a 40t truck between the centroids over a detailed digitised road network (openstreetmap), averaged at the region-pair level. The costs that are considered relate to the truck and the trip itself, such as fuel costs, the driver's wage, maintenance costs, insurance, taxes, road tolls etc. It excludes costs related to storage, cooling or handling.

The sampling approach with many origins and destinations per region allows estimating transport costs both between and within individual regions. It is important to obtain an estimate of transport costs within each region, since on average 75 percent 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 and changes therein will be an important determinant of how changes in transport costs affect the location of economic activity (Ramcharan, 2009; Lafourcade and Thisse, 2011)

Introducing the GTCs into our general equilibrium framework requires considering transport costs in the ad-valorem iceberg-transport cost form, where transport costs are expressed proportional to the value of the shipped goods. To get these iceberg transport costs, we follow Hummels (1999) and Zofío, et al. (2020). We use the sector-specific average value-weight ratio in order to approximate the number of trucks required to ship the observed amount (value) of goods between regions.

The GTCs are transformed into iceberg costs as follows:

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

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 ($\frac{F_{r,r'}}{V_{r,r'}}$) are adjusted from FOB to CIF prices using the International Transport and Insurance Cost of Merchandise Trade (ITIC) database from the OECD.

## 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 programme, amounting to about €30 billion. These ECP investments are mainly destined to the peripheral countries and regions of the Union, as shown by Figure 2 below.

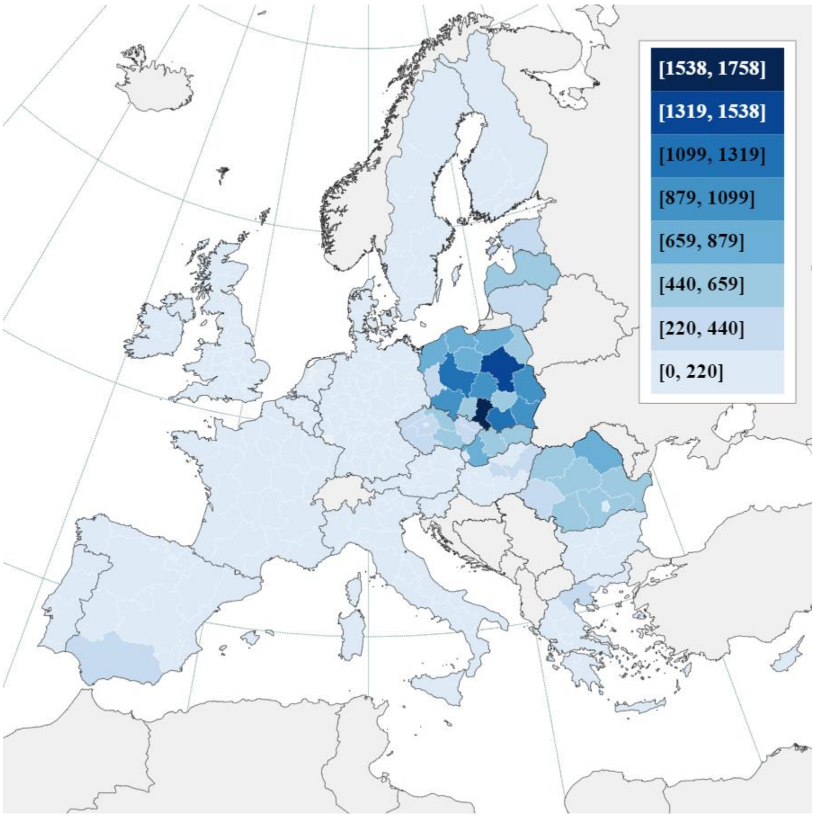


**Figure 2 ECP investment (in millions of €) in road transport infrastructure for the years 2014-2020. Source: DG REGIO**

We use a cost-benefit analysis based on Persyn et al. (2020) 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, a gravity model is used in combination with a geographic information system 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 rank the non-highway roads in each region by the net aggregate economic gain from upgrading the road to a highway, i.e. taking the total estimated traffic on the road and calculating the difference in the cost born by 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 EUR per km (Jacobs-Crisioni et al., 2016), but 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.

The left panel of **Error! Reference source not found.** shows the road segments that have been selected for improvements 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.

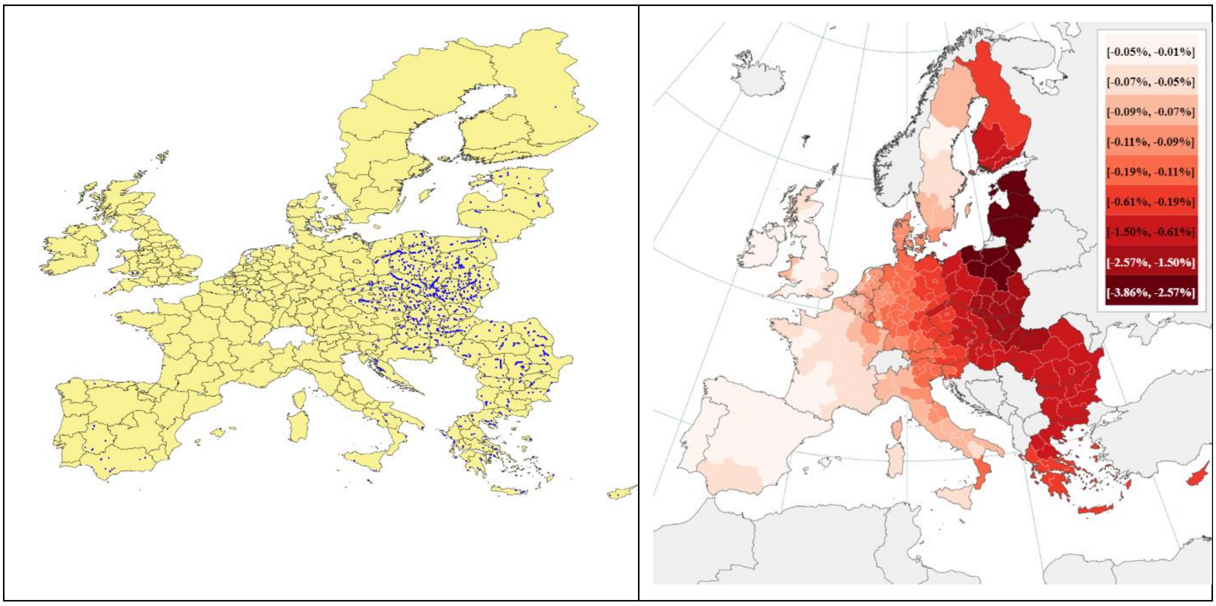


**Figure 3 Left: Roads selected for improvement by the cost-benefit. Right: estimated decrease in the harmonic weighted average transport cost.**

Once we selected the roads to improve, we calculate a counterfactual transport cost matrix that reflects the reduction in transport cost due to the transport infrastructure investment. 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 individual region potentially experiences a change in the transport cost internally and with every of 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.[2]

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. 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 themselves. Of note are the quite strong but localised spillovers in Eastern Germany and Austria.

Our approach allows studying arbitrary amounts of investments in any region, and not only known infrastructure investment projects. It presents some similarities with previous works by Allen and Arkolakis (2019) or Blouri and von Ehrlich (2020). These last 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 as well as those that are passing through. In their framework, transportation infrastructure leads to reductions in 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; or where depending on the location of the improved road link, infrastructure investment may lower transport cost with only specific trade partners and not with others. Moreover, our approach considers the fact that the composition of transport costs and the

[2] **Error! Reference source not found.**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), Persyn et al. (2020), the harmonic average will heavily weigh changes in transport cost 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 predict of changes in trade flows.

effect of investments will differ between localities, depending on infrastructure prices, wages, fuel prices, tolls, etc.

### 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 4 million road segments to rank them for the cost-benefit analysis, and then twice compute the transport costs between a large number of sampled centroids, before and after improving the selected roads. We therefore also 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 267x267 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 267x267 matrix of the total change in transport costs $\Delta$ 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

$$\Delta = \sum_{k=1}^{267} \frac{I_k}{I_k^{ECP}} D_k \tag{5}$$

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 267x267, has been calculated and stored, equation (5) can be used as 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.

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 quite 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 neighbouring region PL62), and the most Northern Swedish region SE33 which borders Finland. Key features from real 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 neighbouring Baltic country of Lithuania, and more northern countries and regions.

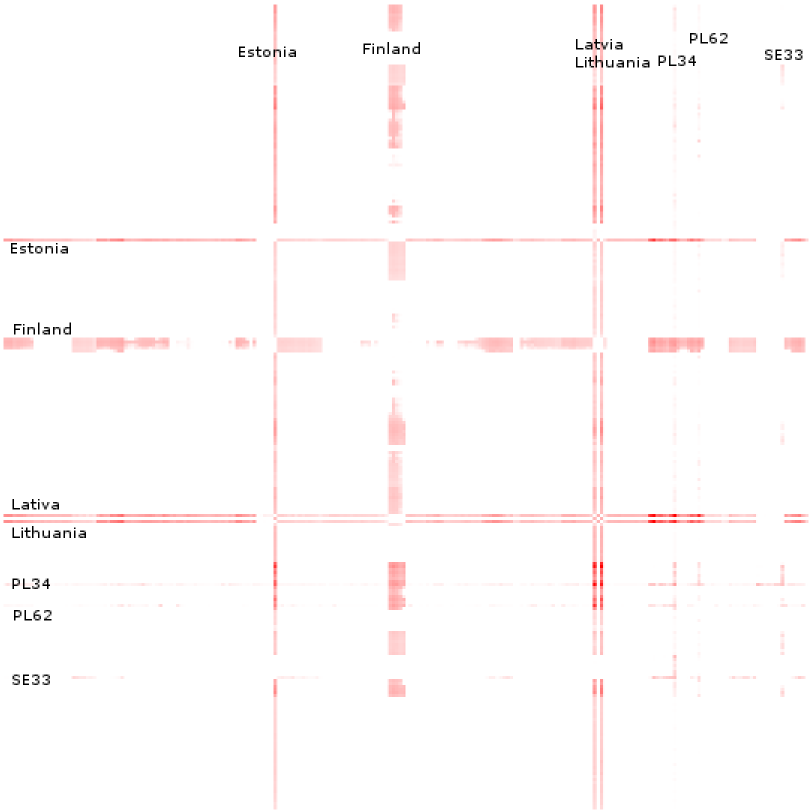


**Figure 4 Heat map of the changes in transport costs due to investments in Podlaskie (PL34) in the north-east of Poland**

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 otherwise hardly affect trade costs in the network.

# 4 The macroeconomic effects of road transport infrastructure investment

This section uses the spatial CGE model with the soft-linked transport model to simulate how various economic variables are affected by the reduction in transport costs.

As explained in previous section, our simulation considers an exogenous permanent reduction in transport costs. The shock is implemented in period one and the model is then run forward until the new long-run equilibrium is achieved where the capital stock in all sectors has fully adjusted. We ignore any other type of shock, such as demand-side effects that would operate through, for example, 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 rather focus on the long-run supply-side effects, 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 labour and capital, directly resulting from the decrease in transport costs.

## 4.1 The effect on trade patterns

The reduction in transport costs lowers the prices of final and intermediate goods, thereby increasing demand of goods by consumers and firms. Regions receiving a large investment in relation to the size of their economy may be expected to increase trade with other EU regions, and especially with the ROW, where commodity prices and transport costs are held fixed. At the same time, regions unaffected by the transport infrastructure investments may experience changes in the relative prices of their exports and imports with the regions in which the investments take place, giving rise to complex system-wide impacts. Moreover, interregional links via labour and capital mobility would also affect the overall effect of the change in transport costs.

We first consider the effect of reduced transport costs on exports. Figure 5 Figure 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, particularly located in Finland, Greece and, to some extent, in France and Germany, enjoying increases in exports despite receiving few or no ECP investments in transport infrastructure. Interestingly, the UK is only marginally affected, excluding a few regions in the north-east of England. The Netherlands, the north-west of Italy and the Castilla-La Mancia region of Spain are almost unaffected with effects below 0.001%. In general, we notice that the magnitude of the effects tends to diminish when moving away from the regions receiving the most funds. 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 of Figure 3 more closely than the geography of investments from Figure 1. This illustrates the importance of taking in to account the geography of trade and transport through the soft-linked transport model. Because of their geographic location, Greece and Finland enjoy large increases in exports from investments that are taking place mainly in Poland and other Eastern European countries. The geographic pattern and size of these effects could only be uncovered by the combination of the CGE and transport model in our framework.

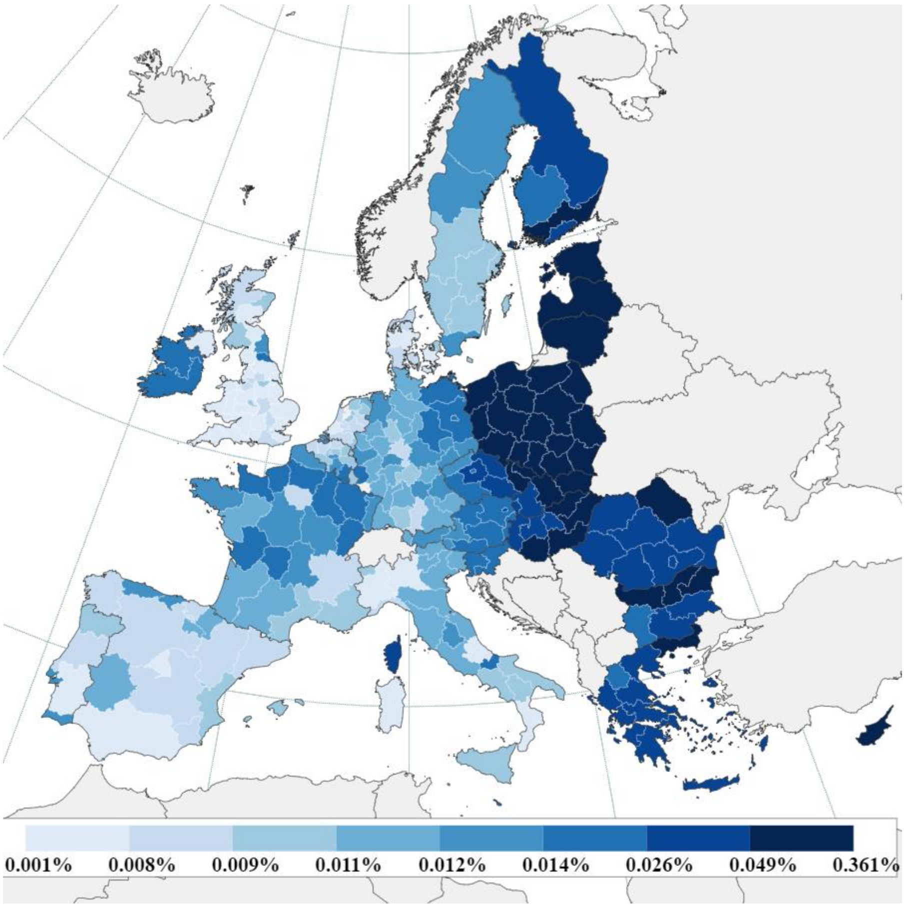


**Figure 5 Changes in total exports per capita due to ECP road improvements (% differences from the baseline values)**

## 4.2 The effect on the spatial distribution of labour and GDP

Figure 6 shows the long run effect of the ECP transport infrastructure investments on migration (left panel) and regional real GDP per capita (right panel).

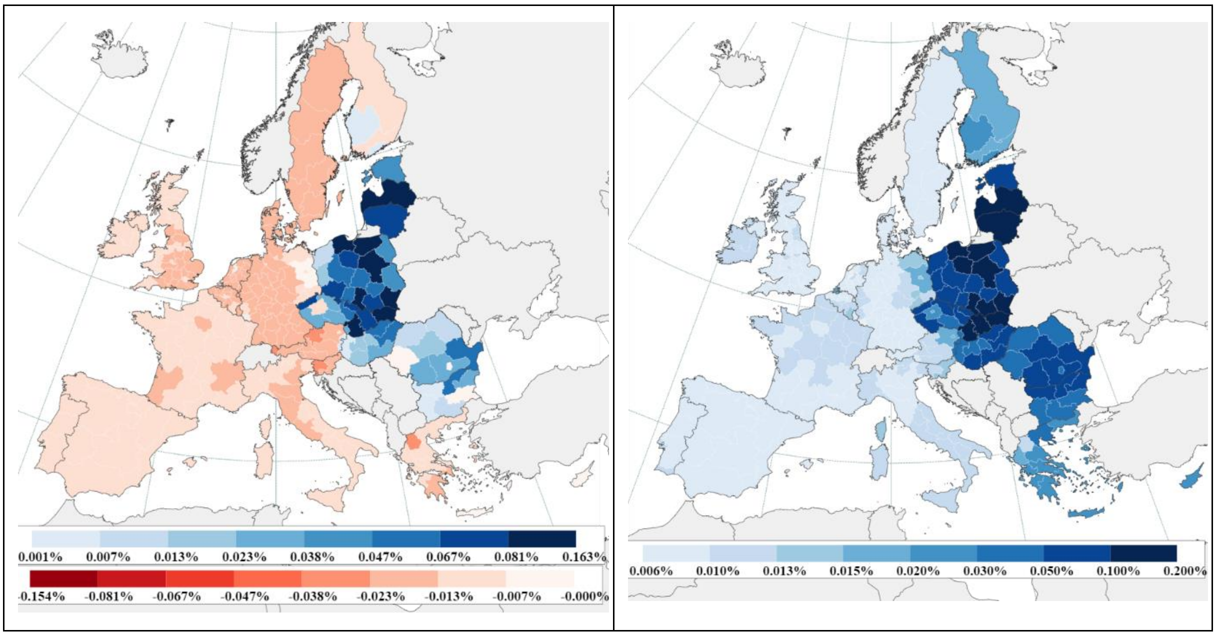


**Figure 6 Left: Change in labour force due to internal migration. Right: change in real GDP per capita**

Adding all the changes in regional GDP for Poland gives an increase of about 767 million euros per year. This compares to an investment of almost 15 billion in the country. There are spillovers to other regions. A country like Austria, for 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 EUR per 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 productivity. Moreover, a key objective of the ECP policy is to reduce inequality, rather than to produce an economic return. Considering that the benefits accrue largely to the targeted regions, with some spillovers mainly to neighbouring regions, our simulations suggest that the lowering of transport costs achieved through the ECP does not lead to a relocation of capital to the economic core, and the largest benefits accrue to the targeted regions. Moreover, the spillovers are large in regions that are mostly outside of the economic core of Europe, such as Eastern Germany, Greece and Northern Finland.

The effects of the transport cost shock on labour mobility reveals a net reallocation of workers towards regions targeted by the investments. Allowing for labour mobility across the EU regions magnifies the effects of transport investments on Eastern European regions, increasing their economic size in terms of GDP and population. As there exists net migration from Eastern Europe, the ECP therefore acts 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 higher changes in labour supply are Śląskie (PL22) and Eastern Slovakia (SK04), both reporting a 0.2% increase in labour supply from initial base year values associated with investments amounting to 6% and 7% of GDP, respectively.

Negative net migration appears in Germany, Austria, Sweden and South England, for example. However, the decrease in the labour supply (and possible impact) in those regions relative to the baseline is quite small.

## 4.3 Spillover analysis

As we showed in **Error! Reference source not found.**, 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 some limited investments in some neighbouring regions such as Eastern Germany or more peripheral regions in, for example, Italy and Spain. In order to study the effects of spillovers in isolation, we therefore consider an alternative "Spillover" scenario, considering only transport costs investments in Eastern European countries, setting the investments in all other regions at zero. In this scenario, any effect observed outside of Eastern Europe is, as a result, a spillover and not a direct effect. The changes in the matrix of transport costs are re-calculated 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, for example, two regions in the south of Portugal, and Ireland).

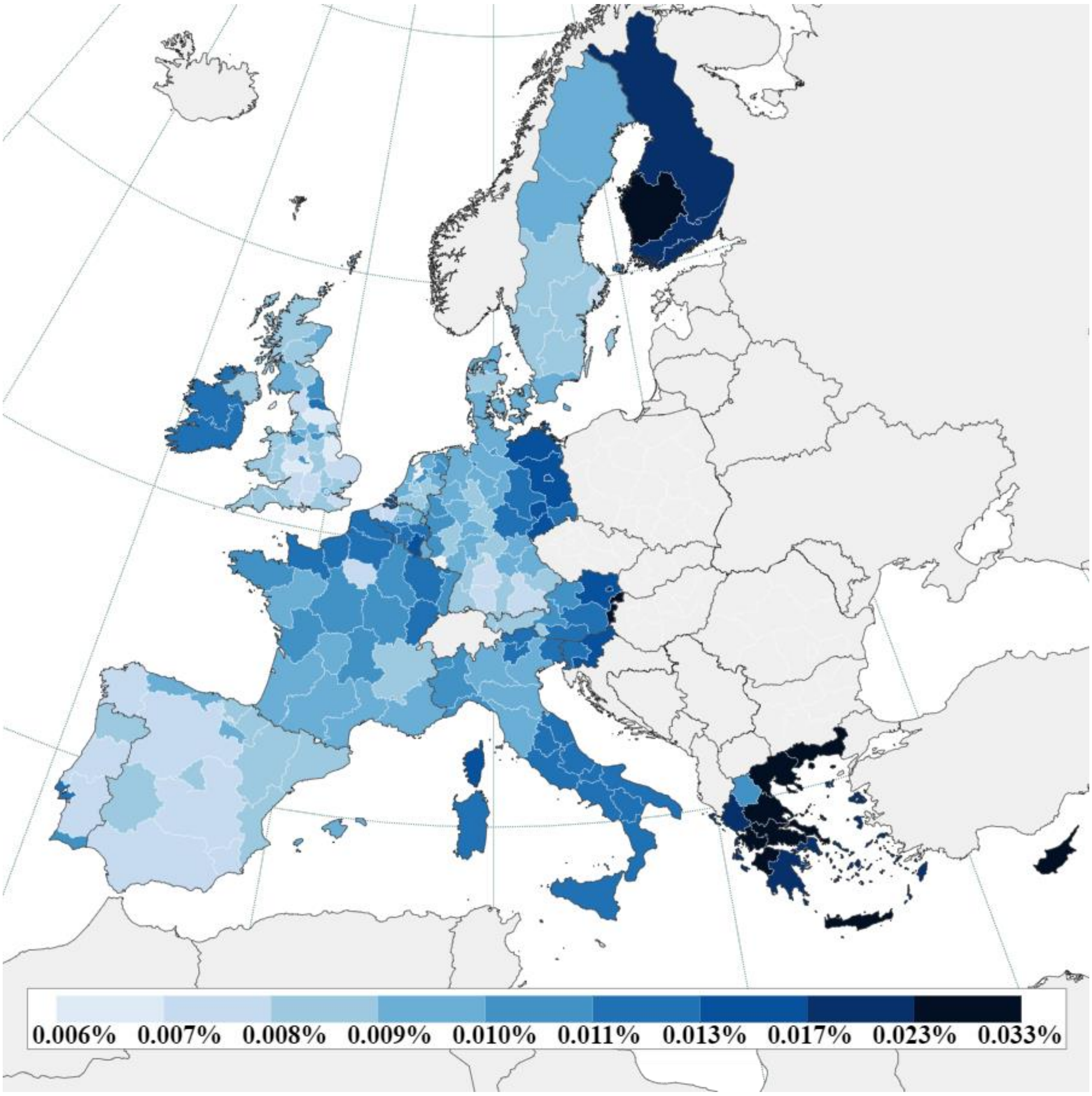


**Figure 7 Long run changes in regional GDP per capita (non-cumulative) - Spillover scenario**

These deviations correlate with the intensity of trade links with Eastern Europe. As we have seen in Figure 1, in general trade intensity with Eastern Europe decreases with distance but substantial irregularities exist. See for instance the effects in southern Portugal shows up in Figure 1 as well as in Figure 7. 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 larger positive effects seen in the heavily industrialised and densely populated Western German Ruhr and Saar regions, compared to Southern Germany, are likely due to a trade mix that is more heavily geared towards the export of basic manufacturing goods, and trade links for such goods that span over larger distances. The next sections will investigate these channels more in depth.

### 4.3.1 International borders and ripple effects.

Although Figure 7 shows that the idiosyncrasies influencing regional spillovers are large, some important regularities exist. First, the effects of 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 each 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 still are hurdles to trade, and this is reflected in the inter-regional 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 northeast 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. Although all regions experience a decrease in trade costs with Eastern Europe, this is more relevant for regions that, 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 is that 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. We now illustrate this emergence of `winners' and 'losers' within countries which 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).[3] 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.

To understand the stark difference in the spillovers experienced by the regions in the East versus the South of Germany visible in Figure 7, Figure 8a shows the changes in exports of the German region of Mecklenburg Vorpommern (DE80), located on the country's Eastern border, to all its EU regional export destinations. We can clearly see that Mecklenburg Vorpommern increases exports to Eastern Europe, but importantly, 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 takes 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 decreases 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.

The spillover effects on GDP reported in Figure 7 highlighted a specific pattern in the effect of investment in Eastern Europe on regional GDP 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[4], compared to the Southern region of Rhône-Alpes (FR71, Figure 8d) which loses export shares in many regions in France and abroad.

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[3] See the appendix B for the exact location of these regions.

[4] But not in the rest of France, due to the fact that the population in these regions decreases slightly, in per capita terms the exports in increase also to French regions.

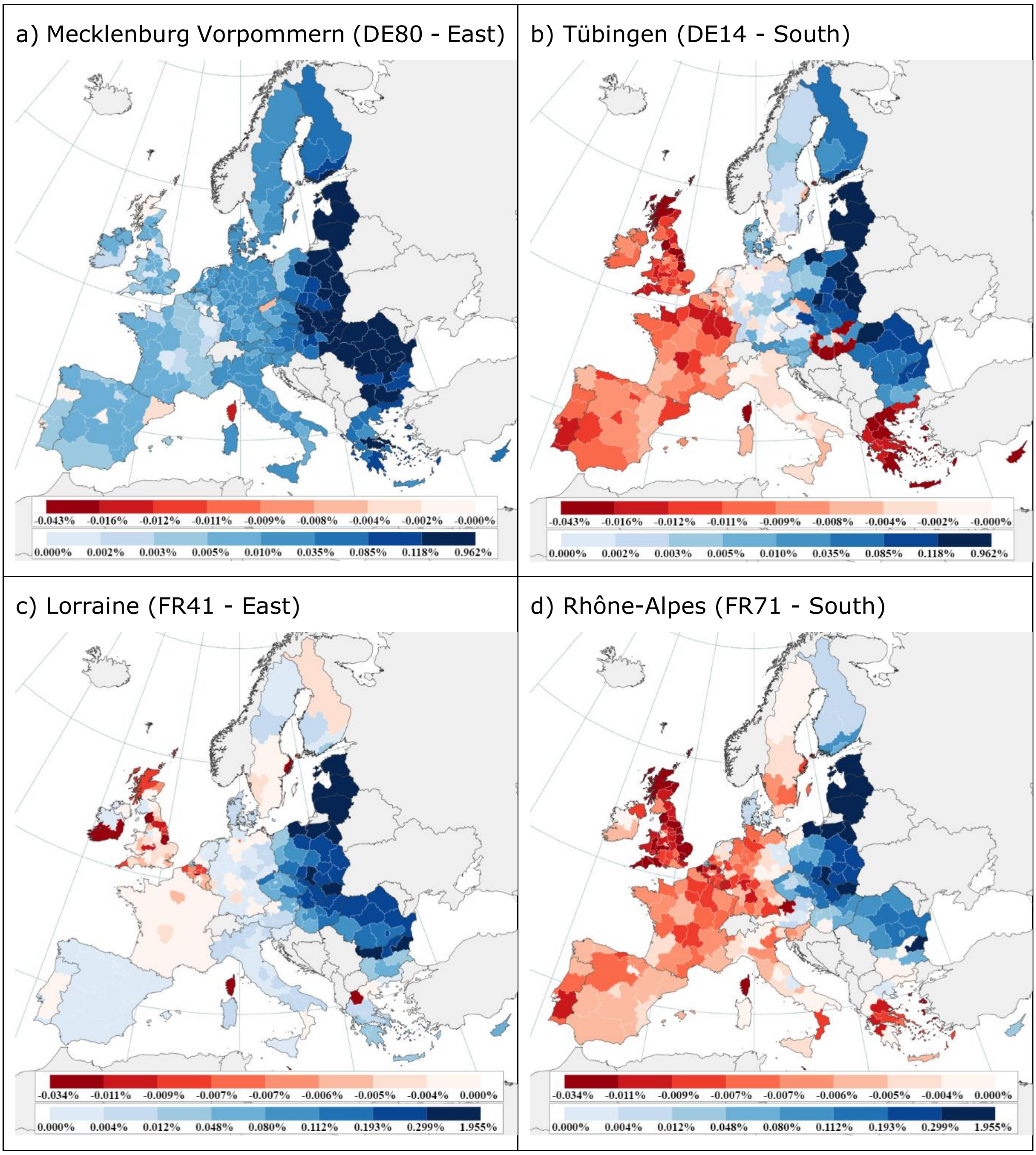


**Figure 8 Changes in exports per capita of four regions (two German and two French)**

### 4.3.2 An econometric analysis of spillovers

The previous sections considered possible mechanisms to explain why the spillovers of large-scale transport infrastructure investment differ between regions. We now attempt to answer this question quantitatively using regression analysis. We consider the following potential explanatory variables in a model with spillovers (measured as the per-capita GDP changes, in logs) as the dependent variable: the weighted average distance from the regions of Eastern Europe (*distance, in logs*); the change in the weighted harmonic average in transport costs of the region (*Tchange*); 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), and we control for trade intensity with all trade partners (*exp* and *imp*).

The results in column (1) of

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| log(distance) | -0.168 *** | | | |
| | (0.053) | | | |
| trade_east | | 1.647 | 4.104 *** | |
| | | (1.022) | (1.053) | |
| Tchange | | -1.594 *** | -1.208 *** | -1.189 *** |
| | | (0.097) | (0.138) | (0.134) |
| imp | | | | 0.291 |
| | | | | (0.235) |
| exp | | | | -0.040 |
| | | | | (0.088) |
| imp_east | | | | 9.799 *** |
| | | | | (2.247) |
| exp_east | | | | -2.432 |
| | | | | (2.248) |
| (Intercept) | -4.255 *** | -4.787 *** | -4.865 *** | -4.925 *** |
| | (0.098) | (0.029) | (0.078) | (0.085) |
| Observations | 213 | 213 | 213 | 213 |
| Country fixed effects | No | No | Yes | Yes |
| $R^2$ / Adjusted $R^2$ | 0.045 / 0.041 | 0.570 / 0.566 | 0.778 / 0.756 | 0.794 / 0.770 |

*Note: Dependent variable is the log of GDP per capita change. Standard errors in parentheses. * p<0.1 ** p<0.05 *** p<0.01*

Table 1 Regression analysis of spillover effects


| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| log(distance) | -0.168 *** | | | |
| | (0.053) | | | |
| trade_east | | 1.647 | 4.104 *** | |
| | | (1.022) | (1.053) | |
| Tchange | | -1.594 *** | -1.208 *** | -1.189 *** |
| | | (0.097) | (0.138) | (0.134) |

| | | | | |
|---|---|---|---|---|
| imp | | | | 0.291 <br> (0.235) |
| exp | | | | -0.040 <br> (0.088) |
| imp_east | | | | 9.799 *** <br> (2.247) |
| exp_east | | | | -2.432 <br> (2.248) |
| (Intercept) | -4.255 *** <br> (0.098) | -4.787 *** <br> (0.029) | -4.865 *** <br> (0.078) | -4.925 *** <br> (0.085) |
| Observations | 213 | 213 | 213 | 213 |
| Country fixed effects | No | No | Yes | Yes |
| $R^2$ / Adjusted $R^2$ | 0.045 / 0.041 | 0.570 / 0.566 | 0.778 / 0.756 | 0.794 / 0.770 |

*Note: Dependent variable is the log of GDP per capita change. Standard errors in parentheses. * p<0.1 ** p<0.05 *** p<0.01*

Table 1 confirm the intuition that regions at a larger weighted geographic distance from Eastern Europe enjoy less spillovers in the form of increases in GDP. There is a spatial gradient in the spillovers, and the western regions that are 10 percent farther from Eastern Europe experience about 1.7 percent smaller increases in GDP. This spatial gradient is small in magnitude, suggesting that the spillovers are quite idiosyncratic, in line with the findings of Figure 7. To analyse whether this idiosyncrasy is due to the trade intensity of individual regions, column (2) replaces distance with an economically more meaningful measure: the baseline trade intensity with Eastern Europe and the change in the harmonic average transport cost of the region. 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. This single variable has an extreme predictive power, as can be seen from the large increase in the $R^2$ compared to the specification of 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 trade intensity with Eastern Europe then becomes highly significant: within countries, regions that are trading more intensively with Eastern Europe benefit more than regions with a lower trade intensity with Eastern Europe. This result confirms the qualitative discussion in the previous section on winners and losers within countries, and that the trade intensity with the east tends to predict which regions gain most *within a country*. Lastly, column (4) of Table 1 separately considers import and export trade intensity. We differentiate between export intensity *exp* defined as exports relative to local GDP, import intensity *imp* equal to imports relative to GDP, and the same variables when only considering imports and exports to Eastern Europe, *imp_east* and *exp_east.* The results show that regions heavily importing from Eastern Europe enjoy an increase in GDP, confirming that it is through cheaper imported intermediates that these regions can gain competitiveness and increase production. The coefficient related to exports is on the other hand not statistically significant at standard levels. Our analysis thus suggests that the ECP-related improvements in transport infrastructure in low-income regions benefits other EU regions, particularly those with a larger backward linkage (also called foreign value-added share of gross exports) with Eastern Europe.

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| log(distance) | -0.168 *** | | | |
| | (0.053) | | | |
| trade_east | | 1.647 | 4.104 *** | |
| | | (1.022) | (1.053) | |
| Tchange | | -1.594 *** | -1.208 *** | -1.189 *** |
| | | (0.097) | (0.138) | (0.134) |
| imp | | | | 0.291 |
| | | | | (0.235) |
| exp | | | | -0.040 |
| | | | | (0.088) |
| imp_east | | | | 9.799 *** |
| | | | | (2.247) |
| exp_east | | | | -2.432 |
| | | | | (2.248) |
| (Intercept) | -4.255 *** | -4.787 *** | -4.865 *** | -4.925 *** |
| | (0.098) | (0.029) | (0.078) | (0.085) |
| Observations | 213 | 213 | 213 | 213 |
| Country fixed effects | No | No | Yes | Yes |
| $R^2$ / Adjusted $R^2$ | 0.045 / 0.041 | 0.570 / 0.566 | 0.778 / 0.756 | 0.794 / 0.770 |

*Note: Dependent variable is the log of GDP per capita change. Standard errors in parentheses. * p<0.1 ** p<0.05 *** p<0.01*

**Table 1 Regression analysis of spillover effects**

# 5 Discussion and conclusion

There is no consensus in the economic literature regarding the size and the direction of the effects to be expected from investments in transport infrastructure on regional and country level development. This paper aims to answer this important research question combining a detailed transport model with a large scale CGE model calibrated with data for all the EU NUTS 2 regions. This detailed modelling framework with many regions captures interdependencies through trade and factor mobility, and sectoral disaggregation taking into account the existence of economies of scale and non-tradables.

As a case we consider the €30 billion of road transport infrastructure investments implemented in the context of the 2014-2020 EU cohesion policy programme, which mainly targeted the less developed regions of the European Union (EU) in Central and 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, but also for countries such as Finland and Greece, which geographic location implies that trade flows cross the countries where road infrastructure is improved. The size of the effect on GDP is significant, considering that we are abstracting from any demand-side effects of the investments. We find positive spillover effects in all the other regions of the EU. We uncover the role played by distance, the existence of national borders, and trading flows in shaping the spatial distribution of these spillovers.

The spillovers create relative winning and losing regions within countries. Using regression analysis on the simulation results we find that, within countries, regions that are trading more intensively with the regions where investments is taking place benefit more. It was found that a high import dependency on the regions targeted by the policy intervention is associated with positive spillovers, whereas export trade intensity has no significant effect and is even associated with a negative effect on GDP. This suggests that regions that are benefitting from larger spillovers are those that obtain cheaper imports, become more competitive and are thus able to increase exports, at the detriment of other regions. This effect can clearly be seen in regions directly bordering the countries where investment is taking place but, perhaps surprisingly, also within countries located quite far from the location of investment, such as France or Spain.

Taken together, our results uncover a rich geography in the direct effects and spillovers generated by transport infrastructure investment. Further research could focus on how our results depend on several modelling assumptions, such as the assumptions on production technology, the structure of the Armington-nests of interregional trade, or the value of trade elasticities.

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## APPENDIX A: The model

### Sets

The model includes 268 regions indexed by $s = 1, \dots, R+1$ of which a subset corresponds to R = 267 endogenous EU + UK NUTS2 regions, which we index as $r = 1, \dots, R$; and one single exogenous region representing the rest of the world.

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 the sectors $\boldsymbol{F}$ is endogenous and determined from the zero-profit equilibrium condition, according to which profits must be equal to fixed costs. The rest of 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, R-U. We assume the following sectors under perfectly competitive market structure: A, O-Q and R-U. The rest are normally treated as imperfectly competitive sectors.

**TABLE A2.** Sectoral classification

| Code NACE Rev. 2 | Sectors description |
|---|---|
| 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 Defence; 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 Organisations and Bodies |

**Households**

Given the consumption of the composite good $C_r$ the household's problem consists in the maximisation of the utility (A1) subject to the budget constraint[5] (A2):

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

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

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

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

where $\psi_r$ is the share of capital income paid directly to households and $\tau_r^w$, $\tau_r^\pi$ are the average rate of labour 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 labour force and unemployment rate. $TR_r$ represents net transfers from government.

Given (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:

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

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 $\sigma^c$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)):

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

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

Saving $S_r$ is determined in fixed share of disposable income:

$$S_r = s_r Y C_r. \tag{A7}$$

**Government**

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

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

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 $\tau_r^w$ and $\tau_r^\pi$, respectively, and indirect taxes on production $Z_{r,j}$ at the rate of $\tau_r^p$. 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.

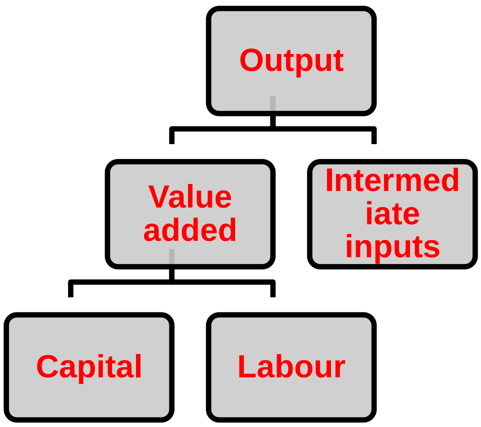


**FIGURE A1.** Hierarchical production structure

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 $V_{r,j}$:

$$Z_{r,j} = Ax_{r,j}\left[\delta^{x}_{r,j}\cdot V_{r,j}^{\rho^{x}_{j}} + \left(1-\delta^{X}_{r,j}\right)\cdot Y_{r,j}^{\rho^{x}_{j}}\right]^{\frac{1}{\rho^{x}_{j}}} \tag{A10}$$

where $\delta^{x}_{r,j}$ 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 $\rho^{x}_{j}$ is the elasticity parameter obtained from the elasticity of substitution $\sigma^{x}$, according to $\rho^{x}_{j} = \frac{\sigma^{x}-1}{\sigma^{x}}$. The corresponding demand equations for *Y* and *V* are described below in Equations (A11) and (A12) respectively:

$$Y_{r,j} = \left(Ax_{r,j}^{\rho^{x}_{j}}\cdot(1-\delta^{x}_{r,j})\cdot\frac{Py_{r,j}}{Pz_{r,j}}\right)^{\frac{1}{1-\rho^{x}_{j}}}\cdot Z_{r,j}, \tag{A11}$$

$$V_{r,j} = \left(Ax_{r,j}^{\rho^{x}_{j}}\cdot\delta^{x}_{r,j}\cdot\frac{PIN_{r,j}}{Pz_{r,j}}\right)^{\frac{1}{1-\rho^{x}_{j}}} Z_{r,j}, \tag{A12}$$

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 follow in Equations (A13) and (A14) respectively:

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

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

$Y_{r,j}$, 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, $\delta^{y}_{j}$ is the share parameter of capital. Substitution between the two types of primary factors is governed by the parameter of substitution $\rho^{y}_{j} = \frac{\sigma^{y}-1}{\sigma^{y}}$ (where $\sigma^{y}$ is the elasticity of substitution between labour 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 sectors *j* from the supplier sector *i*. Input substitution between sectors are 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 below:

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

Given Equations (A13) the demand for capital and labour in each sector $j$, are represented in Equations (A17) and (A18) respectively:

$$KD_{r,j} = \left( \left( (K_{(g)}^d)^{\xi} Ay_{r,j} \right)^{\rho_j^y} \cdot \delta_{r,j}^y \cdot \frac{rk_{r,j}}{Py_{r,j}} \right)^{\frac{1}{1-\rho_j^y}} \cdot Y_{r,j}, \tag{A17}$$

$$LD_{r,j} = \left( \left( (K_{(g)}^d)^{\xi} Ay_{r,j} \right)^{\rho_j^y} (1 - \delta_{r,j}^y) \cdot \frac{W_r}{Py_{r,j}} \right)^{\frac{1}{1-\rho_j^y}} \cdot Y_{r,j}, \tag{A18}$$

where, $rk_{r,j}$ and $W_r$ are respectively the price of capital and the wage rate. For each firms, labour 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′, $x_{r,\prime,j}$, is defined as follows:

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

where, $\eta_{s,s',j}$ is a calibrated expenditure share, $\sigma_j$ 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 Rest of the World), the price $P_{r\prime,j}$ is defined as a CES price index over the market price $p_{r,r\prime,j}$:

$$P_{r,j}^{1-\sigma_j} = \sum_s [\eta_{s,r,j}\, N_{s,j}\, p_{s,r,j}^{1-\sigma_j}] \qquad r \subset s, \tag{A20}$$

where the price $p_{r,r\prime,j}$ set by a firm of region $r$ (net of transport cost $\tau$ and production taxes $\tau_r^p$) 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:

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

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:

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

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

$$P^*_{r,j} = a^y_{r,j} Py_{r,j} + a^{Int}_{r,j} PIN_{r,j}, \tag{A23}$$

$a^y_{r,j}$ 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 parametwrs 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 $I^p$ investments is consistent with the neoclassical firm's profit maximisation 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 $\delta$ 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:

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

$r$, $\delta_r$,$p^I_{EU}$and $rp_r$ denote the interest rate, the depreciation rates, the investment price index at EU level and an exogenous risk premium respectively. $\Delta p^I_{EU}$ 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; $\delta_r$ 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*:

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

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 sectors *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 below in equation (A30):

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

Capital demand equals the capital stock:

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

The labour market is equilibrated:

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

Where labour 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 UK as whole. The number of people migrating from region $r$ to region $r'$ in a given time period t is $L_{r,t}\, z_{r,r\prime,t}$ with $z_{r,r\prime,t}$ the share of these individuals that chooses to move to $r'$ over the time period. The set of possible destinations includes the origin region itself, and therefore $\sum_{r'} z_{r,r',t} = 1$. 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:

$$L_{r,t+1} - L_{r,t} = \sum_{\substack{r' \\ r' \neq r}} L_{r',t}\ z_{r',r,t} - \sum_{\substack{r' \\ r' \neq r}} L_{r,t}\ z_{r,r',t} \qquad \text{(A33)}$$

The migration shares *z* are estimated empirically using a discrete choice framework, with regional income, unemployment, the geodesic distance between the regional geographic centres and international border dummies as explanatory variables (see Brandsma et al., 2014).

The zero profit condition that link output price and average price determine the number of firms in the system for the ***f*** sectors:

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

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

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

**Definition of Equilibrium**. Given initial factors' endowment $\bar{L}_r, \bar{K}^P_{i,}$ 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, labour and capital market, payment account), satisfy the low of motion for private capital and the labour 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 to regional government balance. However, foreign savings from the rest of the world 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 imply that the number of (non-linear) equations to be solved simultaneously is very large (in the order of the hundreds of thousands). Therefore, in order 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, Ivanova, Mandras, & Husby, 2019. The number of firms in each region and sector are 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.

For illustrative purposes, regional average and associated standard deviation of selected calibrated share parameters are reported in Table B1. The structural and behavioural 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, the rate of depreciation is set to 0.15. The risk premium is a calibrated parameter and 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.

**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 |
| Labour 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 |

**TABLE B2** Elasticity parameters.

| | |
|---|---|
| $\sigma^c$ | 0.3 |
| $\sigma^x$ | 0.3 |
| $\sigma^y$ | 0.4 |
| $\sigma^v$ | 0.2 |
| $\sigma_j$ | 4 |
| $\alpha$ | 0 (default case) or 0.1 under dynamic adjustment over wage bargaining |
| $\beta$ | 0.1 |
| $\varsigma$ | 0 (default case) or 0.25 under dynamic adjustment over wage bargaining |
| $\theta$ | 0 (default case) or 0.03 under dynamic adjustment over wage bargaining |
| $v$ | 1 |
| $ir$ | 0.15 (annual interest rate) |
| $\delta_r$ | 0.15 |

For the capital-labour substitution elasticity, the literature provides a wide range of estimates and there is a strong evidence in support of elasticity lower than 1[6] (Krusell et al., 2000; Koesler and Schymura (2015); Okagawa and Ban (2008); Van der Werf (2008); Kemfert (1998); Chirinko, Fazzari, & Meyer (2011); Chirinko (2008); McAdam, & Willman, (2011) ). 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[7].

[6] See Acemoglu (2003).

[7] 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 European dataset derived from the work of Németh, Szabõ, and Ciscar (2011), Olekseyuk and Schürenberg-Frosch (2016) and Aspalter (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 'micro-elasticities' and 'macro elasticities' could be significant (typically the former lower than the latter). This is for example the case of the US (Feenstra et al., 2014; Imbs and

As for the wage curve parameterization, we typically run a long-run wage curve assuming $\beta$=0.1[8] (Nijkamp & Poot, 2005).

The speed of adjustment in the model it 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 the value in the range 0.01–2 while in the study of Caballero and Engel (2003) is in the range of 0.2-2.5.

## Annex C: Data description and further figures

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/km².

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 policy makers that are not bias in one direction.

[8] 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, 1995).


**Figure C2 Selected regions for the analysis of spillovers and ripple effect**

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