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# Regional polycentricity: an indicator framework for assessing cohesion impacts of railway infrastructures

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## ABSTRACT

Territorial cohesion has become one of the main objectives in transport planning. This has fostered the development of assessment methodologies to quantitatively estimate the territorial impact of major transport infrastructures, which are particularly scarce at the intra-regional level. Linked to cohesion, polycentricity has been defined as the best spatial configuration to achieve balanced regions where population and opportunities are distributed among several entities linked by functional relationships. This paper aims to present a methodology to estimate these impacts based on the use of a new regional composite polycentricity indicator. The proposed indicator is tested by comparing the effects of conventional and high-speed railway (HSR) alternatives in the territorial system of a northern region of Spain. This quantitative assessment is a ranking tool for prioritizing rail network alternatives in terms of achieving the most balanced territory, which is especially relevant in countries where HSR networks follow cohesion goals. Our results show that new HSR links should only be complementary to regional railway services, and that the suppression of secondary lines should be avoided if a reduction in polarization is to be achieved.

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Polycentricity; territorial cohesion effects; railway impacts; regional assessment

## 1. Introduction

There is an increasing consensus in European institutions and scientific forums in the need for integrating territorial cohesion objectives into transport planning strategies. Territorial cohesion encompasses and gives spatial dimension to more commonly pursued goals such as socio-economic cohesion and environmental sustainability (Camagni, 2009; Davoudi, 2007; EC, 1999, 2004; Faludi, 2007; Fernández, Pedregal, Rodríguez, Pita, & Zoido, 2009; Golobčič & Marot, 2011; Medeiros, 2013; MF, 2005). As a result, this new concept has gathered strength and there is a growing demand for its inclusion in transport assessment methodologies (Banister & Berechman, 2000; Bröcker, Korzhenevych, & Schürmann, 2010; Grant-Muller, Mackie, Nellthorp, & Pearman, 2001).

Since the negotiation of the Amsterdam Treaty and the release of the European Spatial Development Perspective (ESDP), where territorial cohesion was first mentioned (EC, 1999), many documents, including the recent EU Fifth Cohesion report (EC, 2010),



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50 have tried to define and measure this notion, providing multiple interpretations. The diversity of perspectives and terms usually present in territorial cohesion definitions has caused the concept to remain confusing and ambiguous in both official documents and the scientific literature (Abrahams, 2014; EC, 1999, 2010; EU, 2011; Faludi, 2007; Mirwaldt, McMaster, & Bachlter, 2009). Indeed, it is a complex concept related to equitable distribution of territorial effects which depend on several factors including settlement organization. Medeiros (2011) defined territorial cohesion as a strategy which enhances 'more cohesive and balanced territories by supporting the reduction of socioeconomic territorial imbalances, promoting environmental sustainability, reinforcing and improving territorial cooperation processes and reinforcing and establishing a more polycentric urban system', perhaps providing the most accurate and comprehensive definition of the term.

60 In this sense, polycentricity has been recently presented in European documents as 'the key element for achieving territorial cohesion' at all levels (macro-regional, cross-border and also at national and regional levels) (EU, 2011, p. 7), thus fostering the development of methods to evaluate it. In general, a polycentric region is understood as a group of entities with similar size, proximally spaced and connected by balanced and multidirectional relations among them (Burger & Meijers, 2012; Davoudi, 2003; Green, 2007; Parr, 2004). This type of configuration is thought to ameliorate the negative aspects which are common to agglomerations, such as rising prices, urban sprawl or traffic congestion and emissions related to high commuting flows to the main centres (Veneri & Burgalassi, 2012).

65 However, polycentricity has a multiscalar (intra-, interurban, interregional or international) and multidimensional (morphological and functional) nature (Davoudi, 2003; Ortega, López, & Monzón, 2012; Veneri & Burgalassi, 2012), which complicates its assessment.

70 Indeed, while polycentricity relates to the spatio-functional structure of cities at lower scales, it is also associated with competitiveness issues at interregional ones and with lagging regions and countries at the European level (Brezzi & Veneri, 2015; Meijers, Waterhout, & Zonneveld, 2007). Consequently, assessment goals should be carefully defined in attention to the scale of analysis. For instance, when assessing territorial impacts of high-speed railway (HSR), solutions that may benefit big urban centres connected by HSR may isolate smaller nuclei which will be comparatively disfavoured by the construction of the new railway. Given that new HSR developments have been highly promoted in transport plans where territorial cohesion is the main goal (EC, 2011; MF, 2005), even before or ignoring efficiency criteria, there is a need to stress the fact that such solutions may be counterproductive, especially at lower scales. In fact, the integration of new HSR infrastructures with local and regional services is much more decisive within regions away from major metropolitan areas. In these cases an analysis on how integration is carried out is crucial to achieve cohesion and identify the effects at the regional level (Martínez Sánchez-Mateos & Givoni, 2012; Vickerman, 2014).

85 As a matter of fact, the regional scale has been presented as the 'reference scale' to assess polycentricity at the European level (Fernández et al., 2009). Indeed, polycentricity can be considered a more realistic tool at smaller scales (local and regional), since polycentricity becomes less analytical and more a normative expression with increasing (national and European) scales (Davoudi, 2003). Several studies have focused on the regional scale,

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but on large areas which include the main centres of European countries, such as polycentric urban regions (PURs) of Dutch Randstad, German Rhine-Rhur or South East England (e.g. Hall & Pain, 2006; Kloosterman & Musterd, 2001; Parr, 2004; Van Oort, Burger, & Raspe, 2010). However, almost 80% of the European population lives in regions with less than 1 million inhabitants, while 50% does so in regions with less than 500,000 inhabitants (Eurostat Database, 2015), calling for studies which evaluate transport effects in the configuration of polycentric systems at these smaller scales.

The evaluation of wider impacts, such as territorial cohesion and polycentricity, requires different approaches than traditional and most commonly used cost–benefit analyses (Odgaard, Keely, & Laird, 2005), which are considered insufficient (López, Gutiérrez, & Gómez, 2008). In these cases, multicriteria analysis or the use and integration of specific indicators (Chen & Hall, 2011; López et al., 2008; Martínez Sánchez-Mateos & Givoni, 2012; Monzón, Ortega, & López, 2013; Ortega et al., 2012) become necessary.

The aim of the present study is to contribute to the inclusion of territorial cohesion criteria in the assessment of rail alternatives through the use of a new regional polycentricity indicator. To do so, we propose an indicator based on the morphological dimension of polycentricity and test it by analysing railway alternatives in a region in northern Spain. This comparison enables the estimation of the impact of diverse railway typologies in the future regional territorial configuration, providing a tool for selecting the best alternative in terms of polycentric development.

## 2. Polycentricity evaluation

Polycentricity has been traditionally analysed in relation to two different dimensions: the morphological and functional dimensions (Burger & Meijers, 2012; Green, 2007; Meijers, 2008; Parr, 2004; Veneri & Burgalassi, 2012). Some authors argue that in order to avoid confusion, the term ‘polycentricity’ should address only the morphological dimension and that the term ‘functional polycentricity’ should be used to refer specifically to its functional dimension (Green, 2007; Meijers, 2008), but in general, the term is used indistinctly for both.

The morphological dimension focuses on the specific characteristics of the various entities of the region, and is usually based on their relative size and territorial distribution. On the other hand, the functional dimension refers to the relationships between different centres, their interrelations and interdependencies, and is usually expressed in terms of flows of people, goods, services, information, economic interactions, etc. There are diverging methodologies for polycentricity calculation, some focusing on either one of the two dimensions and others using both of them jointly.

As regards the morphological dimension, most studies use measures related to the size importance of the centres, based on population data. Two techniques are usually present, the log-linear rank-size distribution and the primacy rate (Burger & Meijers, 2012; ESPON 1.1.1., 2004; Meijers, 2008; Meijers et al., 2007; Parr, 2004). The rank-size distribution has been found to be ‘more complete and reliable’ than the primacy rate (Veneri & Burgalassi, 2012, p. 1022). Additionally, the number of units to be considered in the analysis has been a source of debate in the literature, considering the limitations associated with a fixed number of entities (Meijers, 2008; Veneri & Burgalassi, 2012). Most interregional studies focus on the use of functional urban areas (FUAs) as the basic unit of study,

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although other authors, such as Veneri and Burgalassi (2012), claim that municipalities enable a more thorough assessment of regional polycentric development.

As for the spatial distribution of the settlements, which has been much less studied, some scholars refer to the separation of centres, in terms of Euclidean distances or travel times between them (Burgalassi, 2010; Parr, 2004). This separation should be within a range between a lower and an upper limit. The upper limit can be established, for instance, at 1-hour car trip at the regional level (Burgalassi, 2010; Green, 2007).

Studies which are more specifically grounded on the functional dimension are mainly based on network analysis techniques and the use of commuting data. The method proposed by Green (2007) is one of the most commonly used. It is related to the concept of network density of flow data, from Ordinary Polycentricity indicator (OP – only one type of network data) to general functional polycentricity indicator (combined networks). Green's single-networked indicator was also used by Veneri and Burgalassi (2012) along with the Entropy index (EI), the former turning out to be more useful to measure polycentric organizations. However, Burger and Meijers (2012) argued that it is better to avoid network density in the calculation of functional polycentricity and focus instead on analysing the balance in the distribution of functional linkages. This balance is measured by estimating the internal centrality of the region, based on the relative importance of its centres and obtained from incoming flows from other places within the same region.

Other studies are more focused on the use of connectivity measures. De Goie, Burger, Frank, Van Oort, and Kitson (2010) used an extended version of a gravity model that took into account the mass (population or employees) of the settlements, together with the road distances between them, the number of commuters and the node's potential to attract or generate commuting flows. Their results showed that distance has a 'marked inverse correlation' with commuting density, since most people prefer to live relatively close to their working place. Vasanen (2012) proposed a connectivity field method, at the intraurban scale, using measurements of surfaces of interactions instead of using directed commuting flows between predefined nodes. The author argued that this kind of approach provides a more comprehensive way of analysing urban systems.

Some studies are halfway between the morphological and functional approaches. The aforementioned method of Green (2007) can also be included in this category in the case of regional functional polycentricity. The method gives spatial perception to functional polycentricity, in terms of distances or travel times between nodes, to fulfil the rule of settlement closeness for PURs. Similarly, the recent study carried out by Martínez Sánchez-Mateos, Mohíno Sanz, Ureña Francés, and Solís Traperero (2014) provided a regional assessment methodology based on road network accessibility indicators in attention to travel times between nodes. Therefore, although the methodology is considered to be morphological, since accessibility is associated with internal characteristics of the entities (Burger & Meijers, 2012; Martínez Sánchez-Mateos et al., 2014), their results are highly comparable with those obtained by functional approaches and then can be assumed as 'a proxy to interpret the urban network and the potential for spatial integration'.

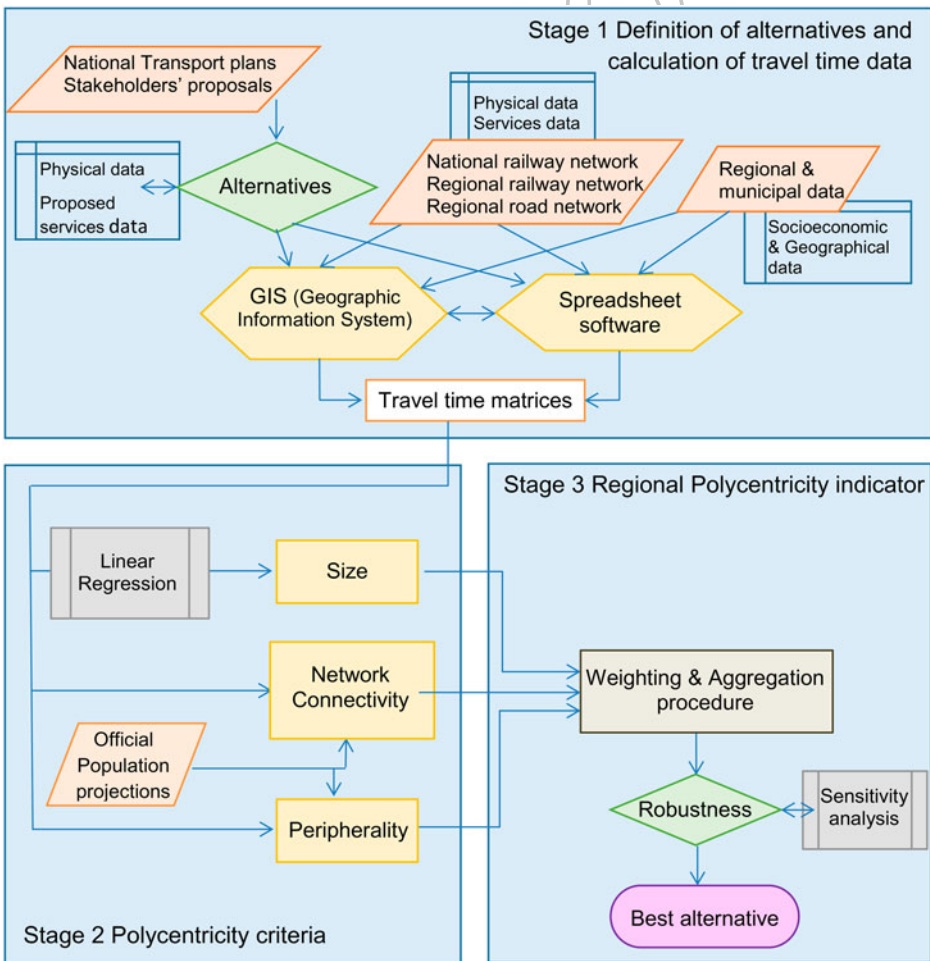
Finally, several studies have claimed the need to analyse both dimensions separately, highlighting the fact that specific measures to assess morphological and functional dimensions of polycentricity are needed (Burger & Meijers, 2012; Veneri & Burgalassi, 2012).

However, these studies have shown considerable correlations between morphological and functional polycentricity, especially when analysing commuting data-based methods, which may indicate that measuring just one dimension is enough to assess polycentricity.

In line with the reviewed approaches, our polycentricity indicator is composed of three sub-indicators: Size, the most representative indicator of the morphological dimension of polycentricity; and Network connectivity and Peripherality, both associated to the spatial distribution aspect of the morphological dimension. These two indicators, based on travel time data, can also be considered a proxy of the functional dimension when commuting data are missing, such as in cases of future projects.

### 3. Methodology

The proposed methodology consists of three stages. Stage 1 involves the definition of railway alternatives and calculation of travel time data. Stage 2 comprises calculation of



**Figure 1.** Three-stage methodology for the regional impact assessment of railway infrastructures through a polycentricity indicator.



the indicators of size, network connectivity and peripherality. Finally, Stage 3 involves the construction of the regional polycentricity indicator and a robustness assessment (Figure 1).

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### 3.1. Stage 1. Definition of alternatives and calculation of travel time data

The process begins with the definition of the various alternatives to be studied and compared, and the calculation of travel time data for each pair of nodes. For a regional assessment, the nodes correspond to the capitals of the LAU level 2 units (Local Administrative Units of the EU's Nomenclature of territorial unit for statistics, formerly NUTS-5 (Eurostat, 2015)). In Spain, for instance, this would correspond with the municipality level, which is the smallest administrative unit with the largest amount of comparable data available (Nogués & González-González, 2014), is stable through time and enables a more thorough characterization of regional development (Veneri & Burgalassi, 2012).

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The premise when selecting the alternatives to be considered is information availability (in order to build the indicators), which should at least cover the number and location of the stations planned, the type and gauge of the lines and the average travel speed and minimum number of daily services the alternative is expected to have.

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Travel times are calculated by modelling a railway network for each alternative and for the current situation in a Geographic Information System (GIS). The regional road network should also be modelled as the connecting mode between nodes and train stations, since not every municipality has a train station. In addition to the municipalities, all the regional capitals in the country (NUTS-3 units) should be considered as destination nodes with a twofold objective:

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- to prevent the appearance of borderline effects related to intraregional accessibility calculations;
- to estimate interregional accessibility values, between the region's capital and the remaining ones, so as to compare territorial cohesion at two different scales.

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The calculation of Origin–Destination (OD) cost matrices is carried out using the GIS program, specifically the Network Analyst package of ArcGIS®, by establishing travel times as impedance parameters. Calculation of complete railway travel times requires data regarding the length and average speed of all the networks' arcs, and is calculated as follows:

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$$t_{O-D}^{\text{rail}} = t_{O-\text{StA}}^{\text{access}} + t_{\text{StA}}^{\text{waiting}} + t_{\text{StA}-\text{StB}}^{\text{rail}} + t_{\text{StB}}^{\text{transfer}} + t_{\text{StB}-\text{StC}}^{\text{rail}} + t_{\text{StC}-D}^{\text{egress}}, \quad (1)$$

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where  $t_{O-\text{StA}}^{\text{access}}$ : access time by road from the origin node  $O$  to the initial train station  $\text{StA}$ ;  $t_{\text{StA}}^{\text{waiting}}$ : penalties for waiting times at the initial train station  $\text{StA}$ ;  $t_{\text{StA}-\text{StB}}^{\text{rail}}$  and  $t_{\text{StB}-\text{StC}}^{\text{rail}}$ : travel times between stations;  $t_{\text{StB}}^{\text{transfer}}$ : penalties for transfer or waiting times at the intermediate station  $\text{StB}$ ;  $t_{\text{StC}-D}^{\text{egress}}$ : egress time by road from the final station  $\text{StC}$  to the destination node  $D$ .

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The results are three OD tables for each alternative which should be combined in a total travel time table. The first table, obtained using the OD Cost Matrix tool, contains travel times between train stations. The second table, obtained using the Closest Facility tool, contains intraregional access and egress times by road to the nearest train station. The

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third one, obtained using the OD Cost Matrix tool, comprises transfer times between conventional and high-speed stations at several NUTS-3 capitals where travellers have to use buses to transit between both types of stations.

### 275 3.2. Stage 2. Indicators of the three polycentricity criteria

#### 3.2.1. Size

280 Size refers to the hierarchical distribution of the population. The rank-size rule (Richardson, 1973) is one of the most accepted and commonly used indicators of size, especially in the Lotka form (equation (2)). It compares the population of the various entities with their rank in relation to the major entity of the region, related to two constants  $\alpha$  and  $\beta$ , where  $\beta$  is negative by construction (Parr, 2004). Our size indicator corresponds to the  $\beta$  parameter (equation (3)). In a polycentric system, the rank-size distribution is log-linear ( $\beta$  equals  $-1$ ) (Green, 2007; Meijers, 2008; Veneri & Burgalassi, 2012); consequently, the flatter the distribution, the more polycentric the region.

$$\ln(\text{Population}) = \alpha + \beta \cdot \ln(\text{Rank}), \quad (2)$$

$$S_{A_x} = \beta. \quad (3)$$

290 In studies where alternatives are compared before their implementation, the use of official projections of population does not differentiate among alternatives, so future population values should be estimated for each alternative. Consequently, each alternative would have its own rank-size rule and  $\beta$ .

295 We propose the use of linear regressions to estimate these values as a function of accessibility. Accessibility indicators can be used to estimate issues such as territorial cohesion or regional economic growth, thus being good indicators of population fluctuations (Gutiérrez, Condeço-Melhorado, & Martín, 2010). Changes in the railway network will modify accessibility considerably, thus altering the territorial structure of the region, the distribution of the population, commercial relationships, etc. (Vicker-  
300 man, Spiekermann, & Wegener, 1999). This methodology provides a good understanding of the effects before the instauration of the adapted or new infrastructures (Nogués & González-González, 2014). It should be noted that the main objective of the estimation is to identify potential population growths or losses caused by the different alternatives in the various municipalities involved, and not to obtain exact future population values.

305 Accessibility values are calculated by a variation of the accessibility indicator proposed by Leake and Huzayyin (1979): the Speed-Route indicator (SR), which compares the real average travel time ( $t$ ) and the theoretical travel time ( $t^0$ ) when following a straight line at the average speed of the rail network (Izquierdo, 2001; Nogués & González-González, 310 2014), as follows:

$$SR_i = \frac{1}{n} \cdot \frac{\sum_1^n t_{ij}}{\sum_1^n t_{ij}^0}. \quad (4)$$

315 Other indicators that integrate attraction factors, such as potential or location accessibility (Gutiérrez Puebla, 2001; Schürmann & Talaat, 2002), are rejected given that, on the one hand, the lack of official projections of economic data such as GDP or employment

would require their calculation, making the process more complex; and, on the other hand, the use of official projections of population would be inappropriate to estimate future population values.

### 3.2.2. Network connectivity

Network connectivity estimates interdependencies between nodes taking into consideration their population values and transport relationships among them, expressed in terms of travel times. In this case, the interdependencies are established by a numerical taxonomic model; that is, an iterative clustering process where each entity is considered as a separate cluster and merged into successively larger clusters, arriving at a single major cluster containing all of them. Although numerical taxonomy has been principally employed in biology, other authors such as Gatti and Cavuoti (1988), Gatti, Cavuoti, and dell'Olio (2002) and Papadaskalopoulos, Karaganis, and Christofakis (2005) proposed the use of taxonomic models to establish hierarchies of centres in relation to transport infrastructures. The studies of Gatti et al. (2002) on the city of Bari concluded that numerical taxonomic models allow understanding the influence/relation of accessibility variations on changes in territorial structure and hierarchy.

Gatti and Cavuoti (1988) proposed an agglomerative dissimilarity index (DC) which compares the mass  $S$  (attraction factor: population, GDP, etc.) of a pair of entities, considering the impedance (distance, cost or travel time) between them,  $d_{ij}$ . The constant  $k$  is a scalar factor that multiplies the final value of DC, which is usually 1. Gonzalo Orden, Rojo Arce, dell'Olio, and Ibeas Portilla (2008) added a constant factor  $\alpha$  which raised the impedance parameter. This factor is calibrated according to the initial data to better represent the territorial dependencies of a specific region. Each municipality accumulated the mass of the lower level entities, obtaining a new value of  $DC_{ij}$ , as follows:

$$DC_{ij} = 2k \frac{S_i S_j}{S_i + S_j} d_{ij}^\alpha. \quad (5)$$

The iterative process can be performed in a programmable calculator in order to obtain the following outcomes:

- the code of the higher level entity where the municipality is absorbed;
- the iteration level in which the entity is absorbed;
- the initial and final masses of the agglomerated municipality and
- the  $DC_{ij}$  value.

The network connectivity indicator is calculated estimating the average regional value of min-max normalized dissimilarity,  $DC'_{ij}$ , weighted by the number of centres that absorb dependent municipalities,  $c$  (equation (6)). Thereby, lower average values of the network indicator are related to lower accumulated masses, and hence to a larger number of centres that have dependent municipalities; in other words, to a more polycentric structure of the region.

$$NC_{Ax} = \frac{\sum_1^n DC'_{ij} \cdot c_i}{\sum_1^n c_i}. \quad (6)$$

### 3.2.3. Peripherality

Peripherality represents the existence of disconnected areas within the region in relation to the quality of the transportation network (intra-regional peripherality) and the connection level of the region with the rest of the country (interregional peripherality), both usually expressed in terms of accessibility.

Most peripherality indicators are formulated as the inverse of accessibility indicators. For instance, Copus (1997) based his peripherality indicator on potential accessibility measures, giving the most central entity, that is, that with the highest potential accessibility, a value of zero, whereas the most remote one had a value of 100. The peripherality index of the remaining centres is obtained by a linear interpolation which is proportional to their potential accessibility (Schürmann & Talaat, 2002).

Potential accessibility indicators integrate an attraction factor (population, GDP or employment) for the journey, as well as an impedance factor, which could be distance, travel cost, travel time, etc. For instance, demographic potential accessibility,  $DP_{ij}$ , considers the amount of population ( $P_j$ ), a node has access to, as a function of the time invested to reach it ( $t_{ij}$ ) (Gutiérrez Puebla, 2001; Schürmann & Talaat, 2002) (equation (7)).

$$DP_{ij} = \sum_j \frac{P_j}{t_{ij}} . \quad (7)$$

To calculate intra-regional peripherality, a normalization of municipal indicator values of DP should be conducted for each alternative. Here, the average regional value represents the predominance of municipalities with higher or lower peripherality values. The higher the amount of municipalities with low peripherality values, the more polycentric the region. In the case of interregional peripherality, the region is represented by the capital city, and accessibility values are obtained by calculating travel time matrices for each pair-wise association of all NUTS-3 capitals in the country. The higher the value of the capital, the more peripheral the region.

The aggregation of intra- and interregional peripherality into a peripherality index is carried out before compiling the polycentricity indicator. Due to the supra-regional character of HSR connections, both indicators are considered equally relevant; thus, the final index is estimated using the average value of both indicators for each alternative (equation (8)).

$$P_{A_x} = 0.5 \cdot P_{\text{intra}_{A_x}} + 0.5 \cdot P_{\text{inter}_{A_x}} . \quad (8)$$

## 3.3. Stage 3. Construction of the regional polycentricity indicator

### 3.3.1. Regional polycentricity indicator

The polycentricity indicator is the result of the aggregation of the regional values of size, network connectivity and peripherality criteria for each alternative. Weighting and aggregation are conducted using the REMBRANDT technique, a multiplicative version of AHP (analytical hierarchical problem; Olson, Fliedner, & Currie, 1995). Criteria weights are obtained from pairwise comparisons among the three criteria according to the REMBRANDT numerical score table (Olson et al., 1995, p. 524). Comparisons are subjective and can be changed depending on the preferences or needs defined by stakeholders. As an alternative to stakeholder interaction, this study proposes a simulation approach

**Table 1.** Linear regression results showing model coefficients, their significance levels and correlations of the dependent variable with each of the predictors.

Model <sup>a</sup>	Unstandardized coefficients		Standardized Coefficients Beta	t	Sig.	Correlation		Collinearity statistics	
	B	Std. error				Zero order	sr <sup>2</sup>	Tolerance	VIF
(Constant)	0.215	.121		1.775	.079				
Log P <sub>1998</sub>	1.018	.021	.947	47.759	.000	.985	.789	.694	1.440
Log SR	−0.862	.249	−0.69	−3.466	.001	−.592	−.057	.694	1.440

<sup>a</sup>Dependent variable: Log P<sub>2011</sub>.  
Note: sr, squared semipartial correlation.

assigning equal importance to the three polycentricity criteria, that is, ‘indifference preference’ according to the score table.

Following Olson et al. (1995), the preference matrix is transformed using the operator  $r_{jk} = e^{0.347\delta(jk)}$ . Criteria weighting scores are obtained from the calculation of geometric means and their additive normalization.

The sign and direction of each criterion in relation to polycentricity need to be reflected within the aggregation into the composite indicator. In the case of Size, values closer to −1 (lower absolute value) are more related to polycentricity. Similarly, lower values of Network connectivity and Peripherality are more related to polycentricity.

Score aggregation into the final polycentricity indicator is achieved by raising each alternative’s performance result (indicator value), to the power of each criterion weight, as follows:

$$\text{Polyc}_{A_x} = S_{A_x}^{0.333} \cdot (NC_{A_x})^{0.333} \cdot P_{A_x}^{0.333}. \quad (9)$$

The final result provides a ranking of railway network alternatives and facilitates the selection of the best option.

### 3.3.2. Sensitivity analysis

The last step of the methodology focuses on validating the proposed model by the application of a sensitivity analysis to the results of the ranking process, specifically to the selection of weights applied to the various criteria. For space reasons, only six additional weighting schemes are considered: three schemes are the result of making a slightly stronger emphasis on each of the three criteria, ‘definite preference’ above the rest, and the other three are the result of applying a ‘strong preference’ for each of the three criteria.

## 4. Case study

### 4.1. Study area

We selected Cantabria, a relatively peripheral region located in central North Spain, within the area known as the European Atlantic Arc, as our case study area. The current Cantabrian railway network comprises both a North–South Iberian gauge (1668 mm) connection and an East–West transversal and continuous metric width connection. Several HSR options have been proposed in this region in consecutive national transport plans since the year 2000, either by the adaptation of existing lines or the construction of new ones. Specifically, Monzón et al. (2013), in their study at the national scale, found that Santander (Cantabria’s

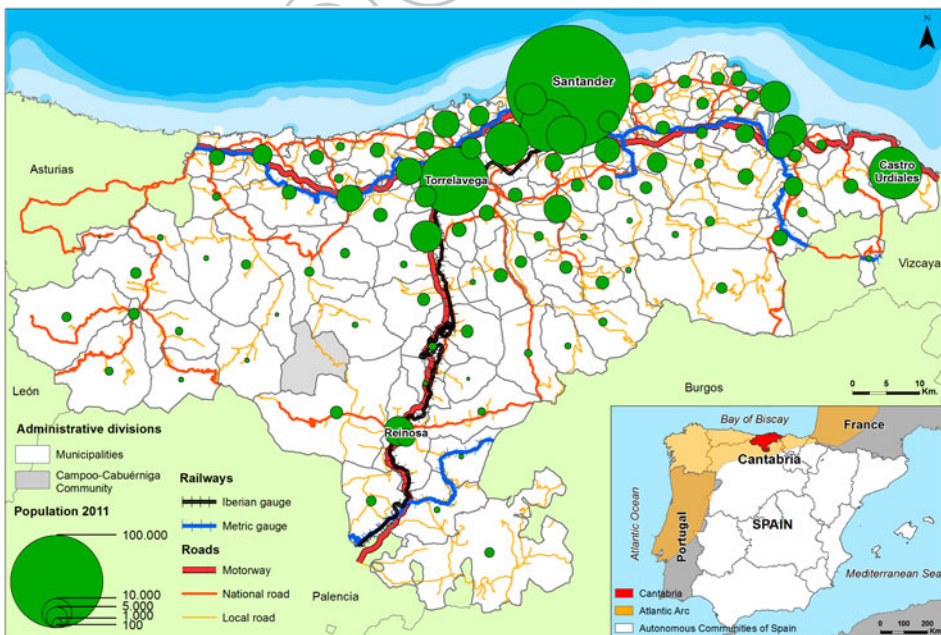
capital) would be one of the cities which would benefit most from the new HSR lines planned in the Spanish National Transport Plan (PEIT, 2005–2020), its accessibility being increased by 99%. The question remains, however, whether this improvement would also be beneficial for other centres in the region, thus enhancing a balanced development.

Furthermore, although the PEIT was deemed as a good opportunity to activate the existing decadent railway system, providing territorial cohesion and better accessibility to all Spanish regions (MF, 2005), the implementation of the new HSR lines has only increased polarization and disparities between Spanish regions (López et al., 2008).

Cantabria, which is classified as a NUTS2-ES13 region, has 592,542 inhabitants (ICANE, 2011), mainly concentrated in the regional capital (Figure 2). The coastal strip and the Besaya river area, linked via the two main transport axes of the region, comprise the urban and productive space, with two main towns: Santander (178,095 inhabitants) and Torrelavega (55,125 inhab.). The eastern towns and villages, especially Castro Urdiales (32,487 inhab.), have been particularly dynamic in recent years owing to their link with the metropolitan area of Bilbao, which is the most important city in Northern Spain. In contrast, the interior valleys represent rural Cantabria, a chiefly depopulated area with a deprived economy, where Reinosa (10,050 inhab.) is the only urban centre.

#### 4.2. HSR alternatives definition and calculation of travel time data

The Cantabrian railway network was ca. 300 km in length in 2011 (base year of the assessment). The North–South connection, entailing the Santander–Palencia line run by RENFE,



**Figure 2.** Regional scheme of Cantabria showing its location, the population of the various municipalities and current railway and road networks.

Note: Campoo-Cabuérniga Community is an administrative division without population which corresponds to a hill of public domain managed by a group of neighbouring municipalities.

links the region with the Centre of the Iberian Peninsula, operating both passenger and freight traffic. The East–West connection is included in the Ferrol–Bilbao line formerly run by FEVE,<sup>1</sup> which is divided into two sections, the Oviedo–Santander and the Santander–Bilbao (including a branch to Liérganes) stretches, supporting basically regional traffic (including commuting traffic). In addition to these lines, the region is crossed by La Robla railway (metric width), uniting Bilbao with Leon. The national network amounted to ca. 11,900 km of conventional lines and 2200 km of HSR lines (MF, 2011). Two HSR lines which connect with the region are currently under construction: the ‘Basque Y’ (Bilbao–Vitoria–San Sebastian) and the Valladolid–Palencia–Burgos–Vitoria line.

We considered five regional alternatives in 2024 (horizon year), which includes a do-nothing and four single-track options (Figure 3): three of them based on the successive HSR proposals included in Spanish transport plans (specifically, the PIT 2000–2007, PEIT 2005–2020 (MF, 2005) and PITVI 2012–2024 (MF, 2013)), and one based on

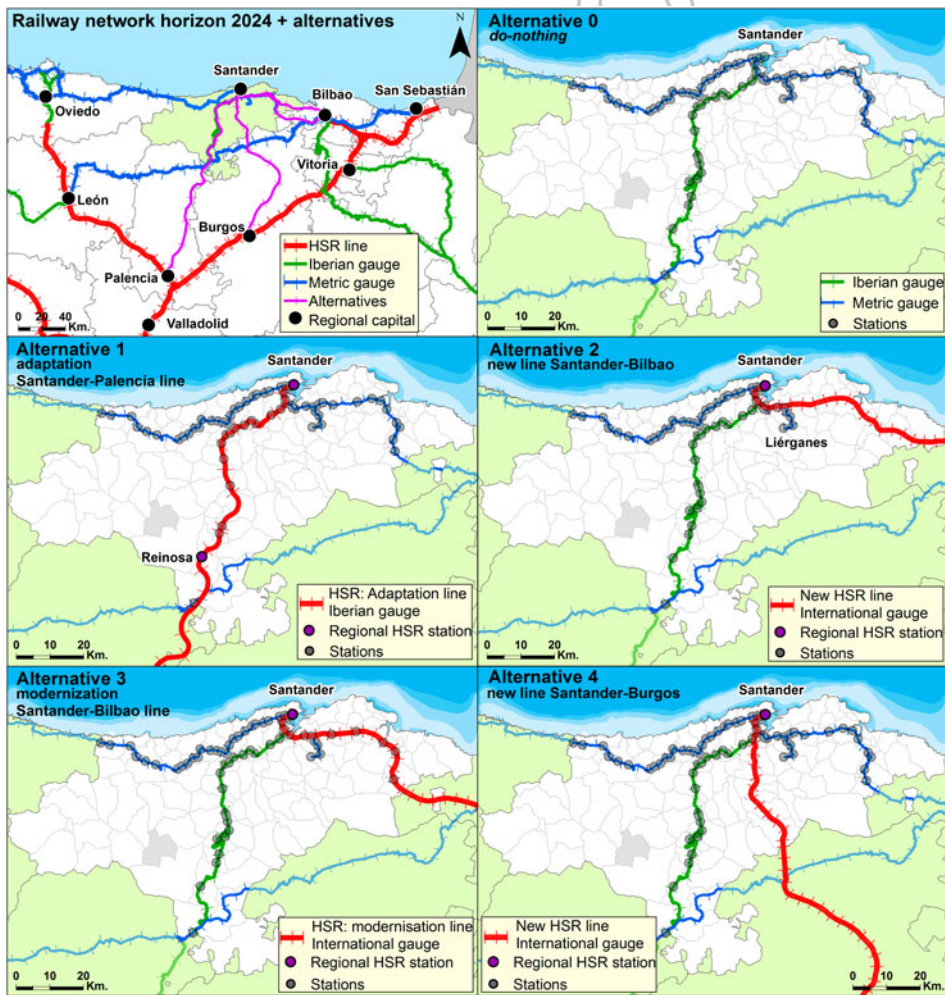


Figure 3. Railway alternatives under study.

several requests from academic experts, which were not considered in the aforementioned plans.

*A0, do-nothing*

This alternative represents what would happen by 2024 if the current network situation would not be altered; that is, with the current regional and national networks plus the conclusion of the lines now under construction.

*A1, an adaptation of the current Santander–Palencia line*

This alternative represents what would happen if completion of the proposed HSR between Santander and Palencia would occur. This option would imply the adaptation of the existing Iberian gauge line, by introducing a new variant between Reinosa and Los Corrales de Buelna, and slightly correcting the current path. The resulting line would connect Santander with Palencia (81,089 inhab.), which is 200 kilometres apart. The maximum speed designed for this line is 250 kilometres/hour. Since it is an adaptation of the current line, regional services would co-exist with high-speed connections (with stops in Reinosa and Santander) along a great part of the path, while mixed services (passengers/freight) would also be preserved. Five of the 72 conventional stations of the region would be eliminated due to the variant.

*A2, a new line to Bilbao*

This alternative involves the construction of a new international width line along the coast between Santander and Bilbao which would substitute the existing one and would have no intermediate stops. Bilbao, which is 108 km away, has ca. 1 million inhabitants in its metropolitan area. The regional service to the eastern part of the region would be limited to the Liérganes–Santander branch, eliminating the 11 stations of the substituted conventional line.

*A3, a modernization of the current line to Bilbao*

This alternative entails a modernization of the existing Santander–Bilbao path and its modification to international width. In this improved line, a direct service to Bilbao would be offered while maintaining regional services, thus preserving the majority of the existing intermediate stops (eight stations were eliminated).

*A4, a new line to Burgos*

The Santander–Burgos HSR, which partly follows the old unfinished Santander–Mediterranean path, would be a new international width HSR line with no intermediate stops. It would connect Santander with Burgos (178,864 inhab.), which is 122 km apart. The rest of the regional connections would be maintained without changes.

The calculation of travel time data involves 147 OD nodes: 102 municipalities of Cantabria and the remaining 45 Spanish NUTS-3 capitals of the Iberian Peninsula. Average travel time values and frequencies for each rail line were established from the timetable information of RENFE for current lines and from times predicted in Feasibility Studies for future lines (including the various alternatives), for both regional and national networks. Waiting times at origin stations were defined as a percentage of the frequency time with a maximum boundary: 50% or 15 minutes for regional trips and 20% or 30 minutes for national trips. Average penalties for each intermediate stop were 1 and 3 minutes for regional and national trips, respectively.



### 4.3. Results of the polycentricity criteria

#### 4.3.1. Size

We selected 1998 as the reference year in the past to establish the same time difference as that between the initial year of our study (2011) and the time horizon for which the alternatives are projected according to the last National Transport Plan (2024) (MF, 2013). Population in 1998 ( $P_{1998}$ ) and Speed-Route in 2011 ( $SD_{2011}$ ) were considered as the potential predictor variables for the regression analysis, while Population in 2011 ( $P_{2011}$ ) was the dependent variable.

Heteroscedasticity involved in the regression was analysed by comparing the standardized residuals and the adjusted predicted values in a scatterplot, and solved by log-transforming non-homogenous variables (Pérez López, 2004). The result of the regression was a model (Table 1) with excellent values of  $R^2$  and an adjusted  $R^2$  (in both cases .972).

$$\log(P) = 0.215 + 1.018 * \log(P_i) - 0.862 * \log(SR). \quad (10)$$

With regard to the estimated population values, A0, the do-nothing alternative, and A1, the Santander–Palencia adaptation line, would increase the population in most municipalities (Figure 4). While A0 would augment the population in the East coast, probably due to the proximity of Bilbao and the ‘Basque Y’ HSR link, A1 would cause this same effect especially in the surrounding area of Reinosa, where a HSR service stop is planned. In contrast, alternatives A2 and A4, the new HSR lines without intermediate stops, would reduce the population of a large number of municipalities, especially in the western and southern areas.

Accordingly, the results of the size indicator show that A0 would promote the most polycentric structure, followed by A1 (Table 2). Conversely, A4 would be the worst alternative, since although it would connect the same number of municipalities as A0, it would strengthen the inequalities among the municipalities close to the Santander area and those in the rest of the region.

#### 4.3.2. Network connectivity

Future population data obtained from official projections of the National Statistical Institute were used as the attraction mass ( $S$ ) of the dissimilarity index. Official data at the regional level were disaggregated at the municipal level using trends of the last 10 years. The impedance factor was travel time data for each alternative. Parameter  $\alpha$  was calibrated according to the initial situation, year 2011, its values increasing 0.1 at a time. The best performance of the dissimilarity index for Cantabria was obtained when  $\alpha$  was given a value of 1.5.

**Table 2.** Performance of the various alternatives under each criterion.

Alternative	Size	Network connectivity	Intra-regional peripherality	Interregional peripherality	Average peripherality
<b>A0</b>	<b>-1.467</b>	11.319	54.636	94.988	74.812
A1	-1.470	11.828	56.356	74.651	65.504
A2	-1.478	14.771	57.619	65.881	61.750
A3	-1.476	14.173	51.017	73.488	62.252
<b>A4</b>	<b>-1.482</b>	<b>11.242</b>	<b>50.768</b>	<b>65.742</b>	<b>58.255</b>

Note: The best results are highlighted in bold.

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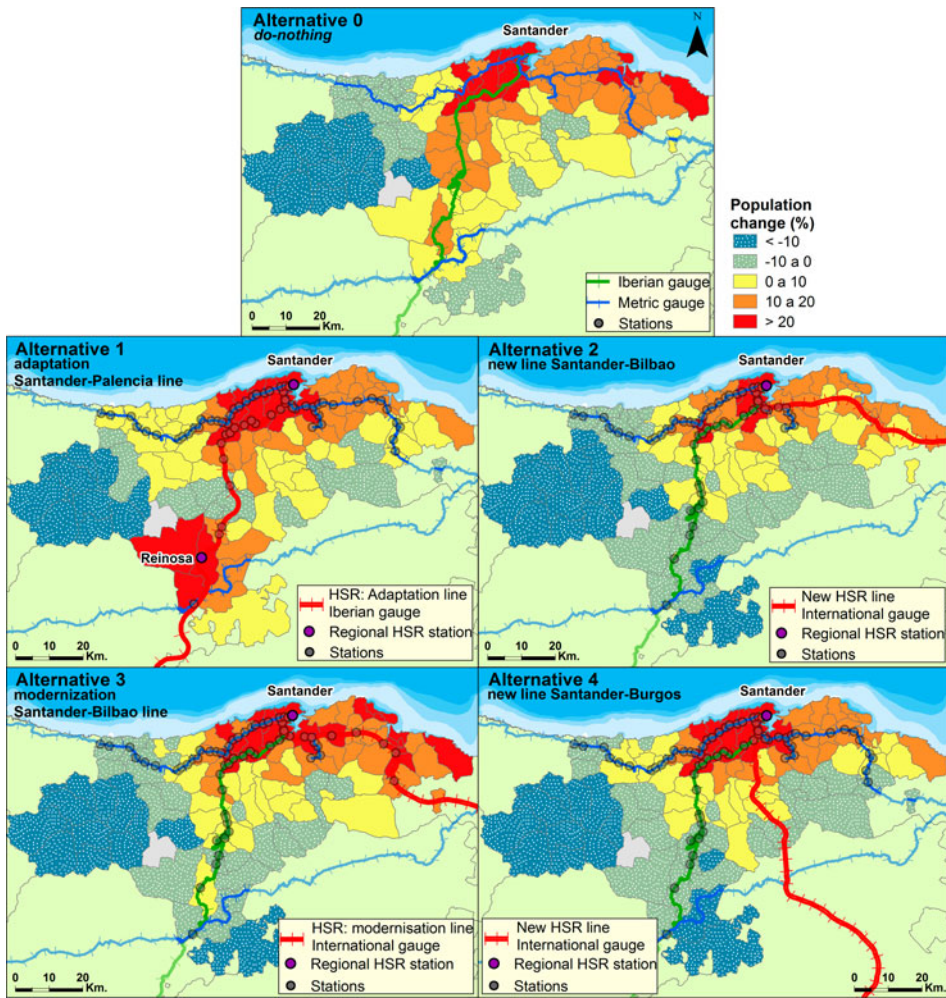


Figure 4. Relative population change with respect to the initial situation 2011.

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$DC_{ij}$  values obtained from the clustering process were used to construct dependency maps for each alternative using the Flowpy Software (ENJ, 2010) to validate the calibration of  $\alpha$  and to understand the changes in dependencies caused by the alternatives (Figure 5). This program produces a shapefile with the net flow of dependencies of a group of entities for each alternative, where the interaction matrix was formed with the  $DC_{ij}$  values, for nodes  $i$  (node to be included) and  $j$  (higher level node).

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Table 3. Results of the calculation of the polycentricity indicator for each alternative

Alternative	Calculation	Value	Rank position
A0	$1.467^{0.333} \cdot 11.319^{0.333} \cdot 74.812^{0.333}$	10.750	3°
A1	$1.470^{0.333} \cdot 11.828^{0.333} \cdot 65.504^{0.333}$	10.443	2°
A2	$1.478^{0.333} \cdot 14.771^{0.333} \cdot 61.750^{0.333}$	11.047	5°
A3	$1.476^{0.333} \cdot 14.173^{0.333} \cdot 62.252^{0.333}$	10.920	4°
A4	$1.482^{0.333} \cdot 11.242^{0.333} \cdot 58.255^{0.333}$	9.901	1°

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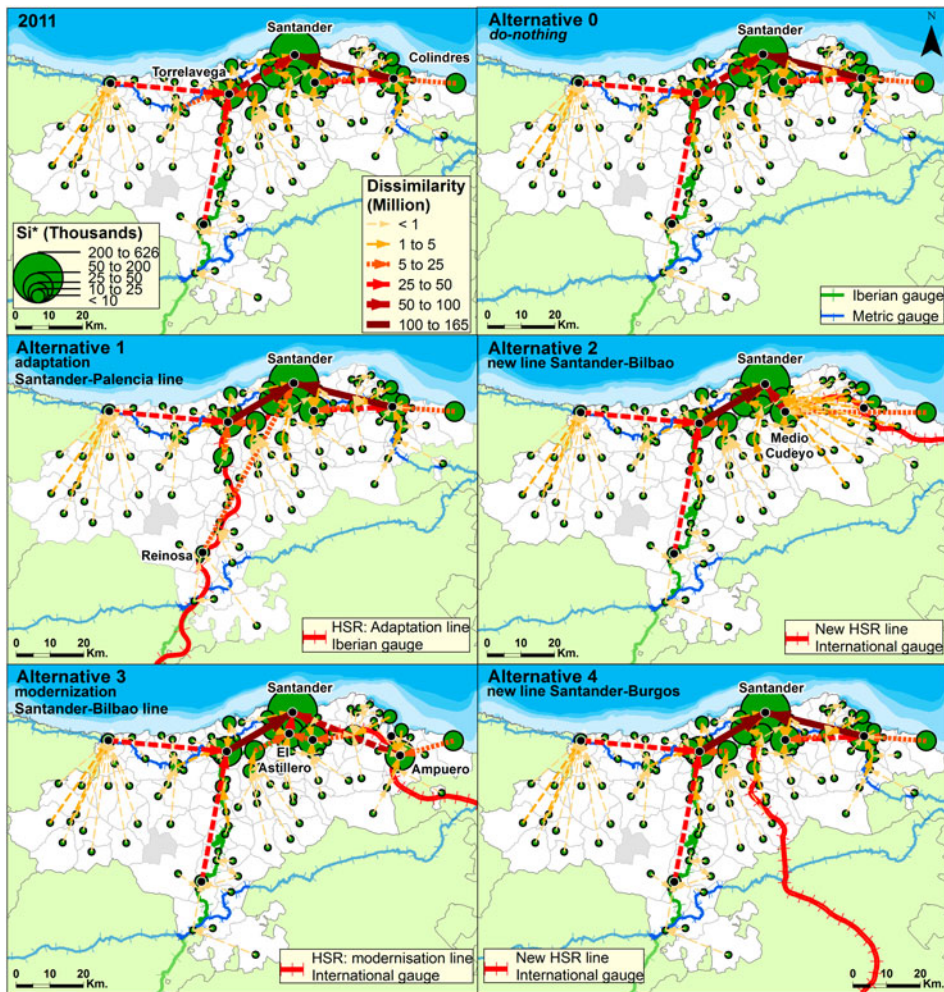
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**Figure 5.** Municipal interdependencies as shown by network connectivity.  
 Note:  $S_i^*$ , accumulated population.

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In all situations, Santander remained as the main node gathering the region's total population, as shown by Figure 5. In 2011 (initial situation), and for A0, the dependency relations were higher and more distributed within the territory, dominated by Santander, Torrelavega and Colindres.

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The dependency index showed a clear relation with the changes proposed in the railway network. In the case of A4, the direct link to Burgos, the dependencies were very similar to those occurring in the initial situation and in A0, except for the increase in net flows from Torrelavega and Colindres to Santander in A4. A1 practically maintained the same structure as A0 and A4, except for Reinoso which would become dependent on the capital city, now directly connected by the adapted line. Similarly, in A3, Colindres would be substituted by Ampuero (the second last stop before Bilbao), as the dominant entity of the eastern area of the region. Moreover, another central node (El Astillero) would increase its importance level, concentrating dependencies near the capital's area.

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The major concentration of dependencies in the central part of the region would occur under A2. Medio Cudeyo gathers a great number of municipalities of the eastern part of the region, as it is the last stop before Bilbao in the traditional rail services, while Colindres would lose its dominant position.

Regarding the regional indicator, when the average regional value was used, A1, the adapted North–South line, turned out to be the best alternative. Close to it, A4, the direct link to Burgos, was the second best alternative. However, when the average value was weighted by the number of dependent entities, A4 resulted the best alternative (Table 2), followed by A0, mainly due to cases such as the aforementioned Reinos. This suggests that a higher number of municipalities connected to the railway network increase the balance relationship between population, distance and connectivity flows. The worst alternative in terms of network connectivity was A2, the direct connection to Bilbao.

### 4.3.3. Peripherality

We used the inverse of the Demographic potential accessibility due to the lack of official or reliable economic or employment future data at the municipal level in Spain.

**4.3.3.1. Intra-regional peripherality.** As expected, Santander was the centremost municipality under the A2 and A4 alternatives, the ones with new HSR links (Figure 6). Under A1 Reinos, where an intermediate stop for HSR services is planned, would be the most central municipality. Under A3, Rasines would be the most central municipality, given that it would be the last stop before Bilbao. Lastly, for the do-nothing alternative, Valdeolea would be the most central municipality in the region, probably due to its rail connection with other regional capitals (Palencia, Bilbao and León).

As regards the value of intra-regional peripherality (Table 2), A4, the direct connection to Burgos, presented the lowest value; that is, the region would have fewer peripheral municipalities than with the other alternatives. In contrast, A2, the new line to Bilbao, would increase regional peripherality, given that it would only improve the accessibility of Santander and its surrounding area, sacrificing that of the rest of the region.

**4.3.3.2. Interregional peripherality.** As expected, the alternatives which integrate new HSR developments, A4 and A2, are the ones that most improve regional accessibility, thus reducing its peripherality (Table 2). A0 was by far the worst alternative in terms of interregional peripherality.

**4.3.3.3. Peripherality index.** The highest differences between interregional values for each alternative compared to intra-regional ones are crucial to the results of the final peripherality index. Indeed, A4 maintained the best performance as it was the best alternative in terms of both intra- and interregional peripherality. This is because it provides new HSR services to the region without sacrificing traditional regional connections, thus establishing a complete and efficient railway network at both intra- and interregional levels. Next was A2, which compensated its worst position in terms of intra-regional peripherality by reaching the second place for interregional values.

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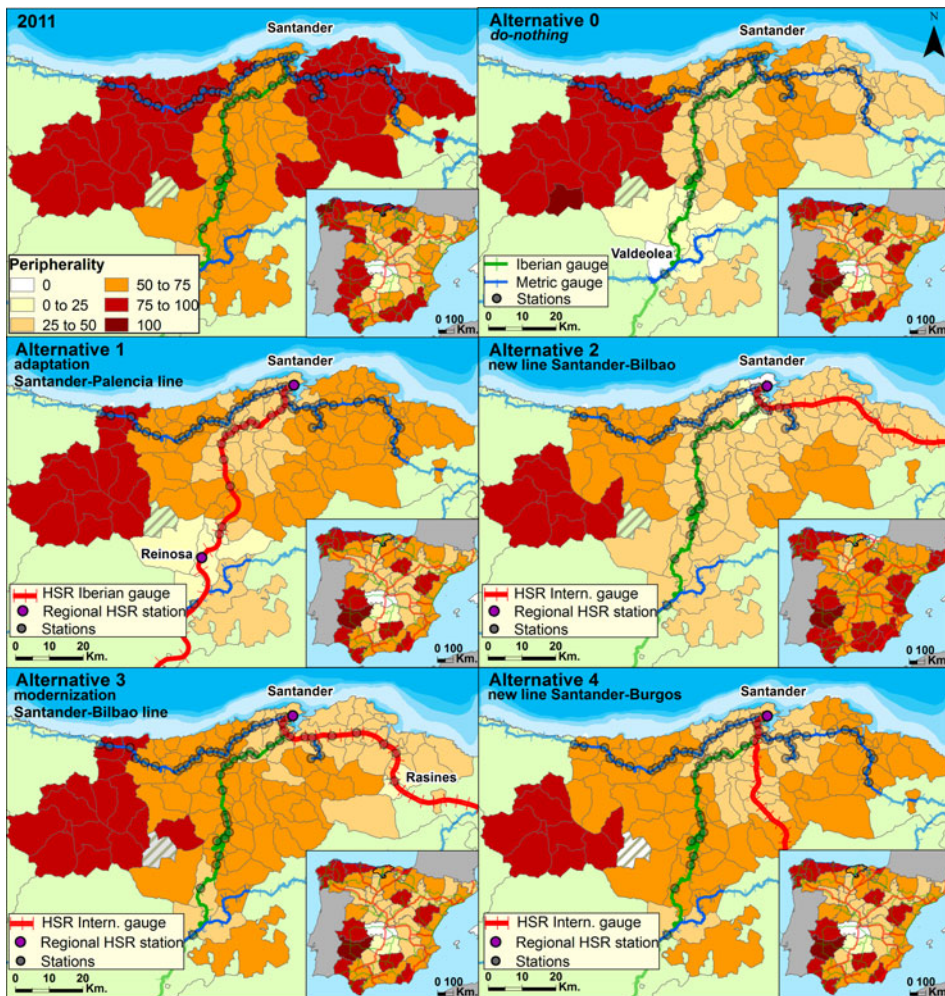
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**Figure 6.** Municipal peripherality as shown by intra- and interregional peripherality indicators.

#### 4.4. Regional polycentricity results

##### 4.4.1. Regional polycentricity indicator

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After applying the final regional polycentricity indicator to each alternative, the ranking of railway network alternatives was  $A4 > A1 > A0 > A3 > A2$  (Table 3). The new link to Burgos (A4) would improve the situation of a large number of municipalities in the centre of the region without reducing the relevance of the remaining areas, since it would maintain conventional services throughout the region. The Santander–Palencia line (A1) would increase the importance of the southern area of the region at the expense of the capital and the northern and central areas, promoting a more polycentric region than alternatives A3 and A2. A3 would reduce the relevance of the southern area while slightly improving the eastern and northern ones. The new direct connection to Bilbao (A2) would be the worst alternative, since it would eliminate current regional services damaging the eastern part of the region in favour of the Santander area.

**Table 4.** Alternatives' performance for the criteria sensitivity analysis.

	IP	DP size	DP network connectivity	DP peripherality	SP size	SP network connectivity	SP peripherality
A0	10.750	3.971	11.031	28.359	2.666	11.145	41.802
A1	10.443	3.918	11.113	26.154	2.647	11.393	37.760
A2	11.047	4.041	12.774	26.118	2.702	13.538	36.848
A3	10.920	4.015	12.441	26.073	2.690	13.107	36.930
<b>A4</b>	<b>9.901</b>	<b>3.831</b>	<b>10.550</b>	<b>24.016</b>	<b>2.620</b>	<b>10.822</b>	<b>34.232</b>

Notes: The best results are highlighted in bold. IP, indifference preference; DP, definite preference; SP, strong preference.

#### 4.4.2. Sensitivity analysis

A4 remained the best alternative for all criteria combinations (Table 4). Likewise, A2 remained the worst scenario for all combinations, except when peripherality was given a 'definite' or 'strong preference' (according to the REMBRANDT score table; Olson et al., 1995) above the remaining criteria; then A0 was the worst alternative. Accordingly, variations in weighting coefficients did not affect the final results significantly.

## 5. Discussion and conclusions

Recent European policies have territorial cohesion as one of their main goals, and present polycentric development as a means to achieve more balanced and sustainable territories (EC, 1999, 2008, 2010). Given the undeniable influence of transport infrastructures in the location and interrelations among cities and regions, assessment methodologies that consider polycentricity evaluations should be included in transport planning processes, along with socio-economic and environmental appraisals.

Conversely to most transport assessments, which basically focus on national and international levels (Givoni, 2006; López & Monzón, 2010; Vickerman, 1997; Vickerman et al., 1999), the main contribution of this paper is a regional polycentric indicator that can be used as a decision-making support tool, enabling the prioritization of railway networks in terms of pursuing more balanced territorial cohesion at an intra-regional level. This regional index considers the aggregation of effects at the municipal level, allowing a sub-regional analysis, which is key to address urban–rural polycentric development problems, as argued by Fernández et al. (2009).

We are aware that some studies question the effectiveness of polycentric development as a policy tool to achieve social, economic and environmental cohesion in its own, and many warn on the lack of empirical evidences to support this effectiveness (Davoudi, 2003; Meijers, 2008; Veneri & Burgalassi, 2012). However, the present study focuses on the assessment of polycentricity as one – but not the only – tool for measuring the territorial cohesion impacts of transport infrastructures.

Moreover, we propose comparing the alternatives of HSR and conventional rail lines prior to their implementation, which has not been much studied before. This comparison permits a more accurate study of planned modifications in railway networks, contrasting likely improvements of long-distance services with the concomitant deteriorations in short-distance services provided by secondary networks, which are very important at the regional level (Chen & De Abreu e Silva, 2013; EU, 2011). This kind of tools is especially useful in times of economic crisis when there are budget constraints and

prioritization of alternatives is needed in order to avoid public investment squander (Nogués & González-González, 2014) and in countries like Spain where political conflicts among regions for transport investments are frequent (Gutiérrez et al., 2010).

As regards the results for Cantabria, the introduction of high-speed services by improving or adapting existing conventional lines that permits coexistence of regional and long-term services provided better results than implementing new direct HSR connections which suppress regional services and only benefit the capital area. This is consistent with the idea that the development of new HSR should carefully consider, and be complemented by, the improvement of secondary conventional networks, instead of responding to projections between major cities, if the disparities created by HSRs are to be avoided (De Goie et al., 2010; Gutiérrez Puebla, 2004; Martínez Sánchez-Mateos & Givoni, 2012; Ortega et al., 2012; Vickerman, 1997, 2014). Secondary networks enable the convergence of the required critical mass to the HSR link, as argued by Gutiérrez Puebla (2004). Therefore, the evaluation of the entire network and the study of its effects at the intra-regional level are essential to better understand the consequences of the HSR implementation.

In Spain, contrary to other European countries such as Germany, which have developed more balanced HSR networks, the choice has been for a network which reinforces a system centred in the capital, Madrid, and its connection with all the remaining provincial capitals (NUTS-3) as an ideal of territorial cohesion (MF, 2005). However, this goal is not only not achieved at the national level, as shown by López et al. (2008), but also entails problems at the regional level. Our results show that the analysis of the territorial effects of infrastructures should be coordinated at different levels, to ensure that more polycentric systems at the national scale do not compromise regional development by concentrating population and activities in a single centre or capital (Meijers et al., 2007). This conclusion, which may seem obvious, has not always been considered in transport policy and does not have a direct application in transport planning.

In summary, when studying polycentricity at a regional level, not only the initial urban system configuration and needs of the region should be considered, but also its planning priorities and data availability. In this sense, the methodology presented here is open to the inclusion of additional modifications by adapting the parameters of the assessment to those certain aspects such as new indicators related to future data or the use of other aggregation techniques. Other variations that may constitute subjects of further research are, for example, the investigation of complementary fields of territorial cohesion, such as environmental assessments and socio-economic cohesion. As a result, this methodology could be easily transferable to other countries and the results extrapolated to other EU regions, especially small peripheral areas which are sparsely populated and face the implementation of new HSR services.

## Note

1. RENFE (Red Nacional de los Ferrocarriles Españoles) is the Spanish National Railway Network company for Iberian gauge railways. FEVE (Ferrocarriles Españoles de Vía Estrecha) is the former Narrow-Gauge Spanish Railways company which has now been absorbed by RENFE.

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