The Journal of Transport and Land Use jtlu.org
Vol. 18 No. 1 [2025] pp. 1–27

JTLU

What drives potential accessibility decomposition? Temporal and spatial variability of the impact of infrastructure and population components in France, Spain, and Poland in the years 1960–2020

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Abstract: Changes in potential accessibility are the effect of both the expansion of transport infrastructure and shortening travel times, as well as land-use processes, e.g., changes in population size and distribution. The aim of the paper is to indicate the spatial and temporal variability of the impact of the infrastructure and population components on changes in potential accessibility in France, Spain and Poland over six decades in the period 1960-2020. The simulations for various parameters of the impedance function presented indicate that in nationwide conditions the greatest improvement in accessibility as a result of the infrastructure component takes place at a specific value of the so-called half-life, predominantly about 60 minutes. For the population component, the length of the trip is less important in assessing changes in accessibility. It has been shown that periods of very high impact of the development of road infrastructure on improving accessibility are mostly limited to a single decade in each of the countries examined, i.e., in the 1970s in France, the 1990s in Spain and the 2010s in Poland. Three approaches to distinguishing typologies have been proposed depending on the use of three dimensions of the interplay of the impact of accessibility components on changes in accessibility. These three dimensions are: (1) the dominance (of strength) of the components, (2) the combination of influence signs of the components and (3) the ratio of the components.

Keywords: Potential accessibility, infrastructure development, population change, France, Spain, Poland

Article history:
Received: April 3, 2024
Received in revised form: August 12, 2024
Accepted: November 6, 2024
Available online: January 22, 2025

https://doi.org/10.5198/jtlu.2025.2508
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The *Journal of Transport and Land Use* is the official journal of the World Society for Transport and Land Use (WSTLUR) and is published and sponsored by the University of Minnesota Center for Transportation Studies.

1 Introduction

Over recent decades, European countries have seen significant improvements in the quantity and quality of modern transport networks, resulting in shortened interregional travel times and improved transport accessibility (Condeço-Melhorado, Martin et al., 2011; Stępniak & Rosik, 2016), understood as the extent to which land-use and transport systems enable individuals to reach desired destinations (Geurs & van Wee, 2004). Intensive investment processes in the construction of highways and expressways, which had already started before World War II in Germany and Italy, accelerated after World War II in most Western European countries. However, their pace and intensity varied greatly between European countries. While in France the development of road infrastructure had already intensified in the 1970s, in Spain a particular boom occurred in the 1990s, i.e., after Spain's accession to the European Union in 1986. In turn, in Central and Eastern Europe (Komornicki & Goliszek, 2023), the big push infrastructure development (Rosenstein-Rodan, 1943) only showed a significant acceleration after the fall of the communist system, i.e., after 1989, and particularly after accession to the European Union, e.g., since 2004 in Poland (Śleszyński, 2021).

The investment processes described above were accompanied by an increase in road accessibility, even though the latter varied spatially and temporally. The number of recent studies that evaluate the spatial distribution of accessibility and its changes across the European continent is quite limited. The notable exceptions are the works by Schürmann and Talaat (2002), Spiekermann, Wegener, Květoň, Marada, Mattern et al. (2015), and Spiekermann, Wegener, Květoň, Marada, Schürmann et al. (2015). Moreover, few studies have investigated multinational accessibility, e.g., in Western (Jacobs-Crisioni & Koomen, 2017) or Central Europe (Jacobs-Crisioni et al., 2016), Iberian Peninsula together with France (Condeço-Melhorado & Christidis, 2018), or several selected countries and regions across Europe (Biosca, Rodrigo et al., 2013). Finally, cross-border accessibility has also been the subject of investigations using examples of Spanish-French (Condeço-Melhorado & Christidis, 2018) or Polish-Slovak (Więckowski et al., 2014) borders. Nevertheless, most research has focused on a single country, examining the internal distribution of potential accessibility between regions or municipalities within a specific country. Geurs and Ritsema van Eck (2003) analyzed accessibility to jobs in the Netherlands, Kotavaara et al. (2001) focused on the interrelation between accessibility and population change in Finland, Cascetta et al. (2020) examined the interplay between economic growth, transport accessibility, and social impacts in Italy, while Axhausen (2008) used the Swiss situation to discuss accessibility in the context of long-term transportation planning.

The studies usually apply the potential accessibility approach, which implies that a greater significance is placed on larger centers compared to smaller ones, and it recognizes a decrease in attractiveness for destinations located at greater distances (Hansen, 1959). Results of the potential accessibility analyses can serve as the foundation for various types of studies. For instance, they can be used to assess regional economic development (Rokicki & Stepniak, 2018) and to conduct analyses of territorial cohesion (Condeço-Melhorado, Gutierrez et al., 2011; Stępniak & Rosik, 2016). In equity studies, the potential accessibility has been used to evaluate the fair distribution of transport services among different population groups (Martens et al., 2012). Moreover, it can be used to evaluate land-use and transport policies (Geurs et. al, 2010), to investigate transport disadvantage and social exclusion (Delbosc & Currie, 2011), to study the relationship between population change and accessibility (Kotavaara et al., 2011), or to analyze the impact of land use and transport component on changes in accessibility (Condeço-Melhorado et al., 2017; Stępniak & Rosik, 2018).

Assuming population as an attractor in the potential model, changes in accessibility in individual regions were caused, on the one hand, by an improved quality of transport networks and the spatial distribution of investments (transport component; cf. Geurs & Ritsema van Eck, 2001), and, on the other hand, by demographic changes (land-use component), both in the form of an increase/decrease in the total population in the country/region and, most frequently, the spatial concentration of population in agglomerations and the depopulation of external peripheries (at national borders) and internal peripheries (at the borders of administrative regions) (Szmytkie, 2022). Comparison of the effects of road infrastructure development on changes in accessibility depending on the mutual interactions between accessibility components in both Western and Central European countries makes the topic discussed important not only in terms of methodology, but also in terms of application.

The aim of the paper is to indicate the temporal and spatial variability of the impact of both components, i.e., population and infrastructure, on the change in the level of potential road accessibility for six individual decades and for the entire period 1960-2020 in France, Spain and Poland. From this perspective, it is interesting to compare the effects of transport infrastructure development in three countries, namely France, Spain, and Poland, where the most significant investment booms occurred approximately two decades apart, while simultaneously having different trajectories of population dynamics and spatial distribution. Our methodological goal was to distinguish the effects related to the land-use component (population component) and the transport component (infrastructure investments), rather than changes resulting from regulations (e.g., speed limits), the increase in the number of cars (changes in congestion), or geopolitical changes (changes in waiting times and border regimes, e.g., at the Poland-Germany border).

In decomposing the effects of changes in accessibility, we paid particular attention in the article to one of the dimensions of accessibility, which is distance decay. The use of different distance decay functions, including the power function, Gaussian, and others, is the subject of many articles on accessibility, such as in Östh et al. (2014) and Martínez and Viegas (2013). In their accessibility studies covering Germany, Reggiani et al. (2011a, 2011b) applied the exponential function in their potential models, paying particular attention to accurately estimating the β parameter for commuters. From a methodological perspective, cohesion analysis and the impact of distance decay on accessibility results in Spain, the works of Condeço-Melhorado, Gutiérrez et al. (2011), Condeço-Melhorado, Martín et al. (2011b), and Condeco-Melhorado et al, (2017) merit particular attention. Nevertheless, to the best of the authors' knowledge, there is currently no study showing the effects of the impact of land use and transport components on changes in accessibility over a long period of time depending on the parameterization of the distance decay function. There is not only a lack of comparative analysis between countries but also a lack of a study for a single country where the analysis simultaneously addresses the impact of decay on changes in accessibility as a result of changes in both land use and transport components of accessibility. Therefore, the added value and novelty of the paper lie in the selection of the appropriate parameter for the distance-decay function, based on the so-called half-lives, which was determined through a series of simulations assessing the impact of population and infrastructure components on improving accessibility.

An additional methodological goal was to develop three methodological approaches to the typology of regions taking into account three dimensions of analysis to varying degrees: (1) the dominance (of strength) of the components, (2) the combination of influence signs of the components and (3) the ratio of the components. At the last stage, the variability of results over time, both at the national level and at the NUTS3 level, was presented for each typology. The proposed new indices of the interplay of accessibility components, along with showing their variability over time, fill the gap in the existing literature on the subject.

In summary, the contribution of the paper and its novelty have a threefold nature. First, we are the first to analyze changes in accessibility over a long period (six decades) simultaneously for three large European countries. Second, we examine the impact of distance decay parameterization on the significance of both components (land use and transport) for changes in accessibility. Third, we propose three new approaches to the typology of regions based on the use of three original indices of interplay between accessibility components. We believe that our approach will be of interest both to researchers and policymakers dealing with accessibility in a historical perspective, and methodologically, it will open new possibilities for the decomposition of potential accessibility changes using distance decay parameterization.

2 Methodology

2.1 Potential accessibility formula and accessibility components

There are many possible approaches to calculating accessibility, including: travel cost approach, daily or cumulative accessibility and potential accessibility (cf. Baradaran & Ramjerdi, 2001; Bruinsma & Rietveld, 1998; Geurs & Ritsema van Eck, 2001; Geurs & van Wee, 2004). There are also more methodologically advanced approaches, such as the activity-based approach (Dong et al., 2006) or the increasingly popular perceived accessibility (Lättman et al., 2016; Pot et al., 2021). A good solution to evaluating long term accessibility changes at the national and regional level, is to use the potential accessibility model, which is often also used to show the effects of transport investments (Gutierrez et al., 2011; Stępniak & Rosik, 2013) or the effects of long-term infrastructure development programs (Holl, 2007; Spiekermann et al., 2015a). For this reason, in this paper we rely on the potential accessibility model, which, as Geurs and Ritsema van Eck (2001) point out, is composed of two components: land-use and transport in accordance with Formula 1:

$$A_R = \sum_r f_1(P_r)\, f_2\left(t_{R,r}\right) \qquad (1)$$

where A_R is the accessibility of transport zone R, the land-use component is represented by the activity function $f_1(P_r)$ the population accessible in the transport zone r (P_r) is a proxy of destination attractiveness, the transport component is represented by the impedance function $f_2\left(t_{R,r}\right)$ and $t_{R,r}$ is the travel time between transport zones R and r. Additionally, the value of A_R is enlarged by a so-called "self-potential," i.e., the potential produced by the unit itself. The calculation of the self potential is performed separately for each transport zone based on the formula proposed by Rich (1978) (See also Gutiérrez et al., 2011; Keeble et al., 1982), where the key is to estimate the internal travel time, i.e., (t_{R,R,d_i}; see Formula 2). The area of the transport zone is likened to a circle, the average travel distance is half the radius, and the assumed internal travel speed is 40 km/h (Kotavaara et al., 2011). Additionally, we assumed that there are additional penalties related to access/egress time (Gutiérrez, 2001), which equaled the half of internal travel time (see the discussion on different approaches regarding self-potential and penalties in Stępniak & Jacobs-Crisioni, 2017).

2.2 Comparative analysis of the level of accessibility between countries over a long period of time

Our paper is part of a long tradition of analyzing accessibility changes in a dynamic approach at the national level (a short survey of this type of analysis is found in Stępniak & Rosik; 2018, Table 1). Some authors examining the impact of components take into account and compare the impact of both of them on changes in accessibility, e.g., Condeço-Melhorado et al. (2017), Lopez et al. (2008) for Spain or Geurs and Ritsema van Eck (2003) for access to jobs in the Netherlands. In other analyses, the authors focus on the joint impact of both components, e.g., Kotavaara et al. (2011) for Finland and Holl (2007) for Spain, as well as Axhausen et al. (2011) for Switzerland. Most analyses are based on a low level of data aggregation, most often the municipal level, although the NUTS3 unit level is also used, in particular with long time series, e.g., for the comparably long period of 1960-2010 in Condeço-Melhorado et al. al. (2017). To the best of the authors' knowledge, all analyses to date have focused on long term changes in accessibility in one country, without international comparisons, perhaps except for Condeço-Melhorado & Christidis (2018), where, however, the differentiation of the role of components in accessibility changes in France, Spain and Portugal was not studied.

Accessibility at the international level is much more often studied in terms of European or cross-border accessibility (Jacobs-Crisioni et al., 2016; Jacobs-Crisioni & Koomen, 2017; there is a review of this type of analysis in Spiekermann, Wegener, Květoň, Marada, Schürmann et al, 2015). An exception is the compilation of accessibility analyses in the form of a case study as part of the ESPON TRACC project (Spiekermann, Wegener, Květoň, Marada, Mattern et al. (2015); Biosca, Spiekermann et al., 2013), where an accessibility study was prepared for some countries and regions of the ESPON space, including the West Mediterranean region (Spain and France) and Poland among others, with the use of six accessibility indicators, including regional potential accessibility and potential accessibility to basic health care. In addition, a comparative analysis of the level of intra-national accessibility was carried out by Rosik et al. (2020) for all countries in Europe in the context of the potential quotient to GDP and in the context of closing national borders by Rosik et al. (2022).

2.3 Parameterization of distance decay. Half-lives

The potential accessibility model takes into account all relations between pairs of transport nodes within countries, taking into account (1) the greater importance (measured by population for the land-use component) of larger centers/transport zones than of smaller ones, and (2) the decreasing attractiveness of the destination as the length of the trip increases (Hansen, 1959; Harris, 1954). We use the exponential function (see the discussion on the adequacy of the choice of the impedance function at the national level in: Rosik et al., 2015), and the accessibility index is calculated for all transport zones (NUTS3) in each of the chosen EU states for every decade according to the Formula 2:

$$A_{R,d_p,d_i} = P_{R,d_p} \exp\left(-\beta t_{R,R,d_i}\right) + \sum_r P_{r,d_p} \exp\left(-\beta t_{R,r,d_i}\right) \quad (2)$$

where:

R – index of the region under consideration;

r – index of the other regions in the country in which R lies;

d_p – index of the decade of population measurement;

d_i – index of the decade for the infrastructural network;

P_{R,d_p} – population of R measured in d_p;

t_{R,r,d_i} – travel time between R and r using the infrastructural network in d_i.

$P_{R,d_p}\exp(-\beta t_{R,R,d_i})$ is the value of the self-potential of region R, and
$\sum_r P_{r,d_p}\exp(-\beta t_{R,r,d_i})$ stands for the sum of potentials resulting from all other NUTS3 regions in the EU state that is being analysed. When calculating the average accessibility for the entire country, the average accessibility of all transport zones is taken into account, weighted by the number of people living in these areas. Therefore, it is the average intra-national accessibility of a resident of a given country, which we refer to as the absolute accessibility of a given country (see Formula 3).

$$\overline{A_{c,d_p,d_i}} = \frac{\sum_{r=1}^{n}\left(P_{r,max(d_p,d_i)} \times A_{r,d_p,d_i}\right)}{\sum_{r=1}^{n} P_{r,max(d_p,d_i)}} \tag{3}$$

where:
n – number of the regions in the country c.

Accessibility results are sensitive (Spiekermann & Neubauer, 2002) to the value of the β parameter (Formula 2). The more locally we examine regional or local differences in accessibility, the shorter the trip length and the steeper the distance decay (with higher β values). Following Östh et al. (2014) and Stępniak and Rosik (2016) we use the so-called "half-life" approach. According to this concept, the attractiveness of the travel destination is reduced by half for the assumed value of the β parameter. This approach posits that a typical (median) trip length ($\bar{t}$) for a specific purpose should be achieved when the attractiveness of the destination is reduced by half, recalling the radioactive isotope Carbon-14 which is commonly used for dating organic materials, as shown in Formula 4:

$$-\beta = \frac{ln(0.5)}{\bar{t}} \tag{4}$$

A similar approach was taken by the ESPON TRACC study (Spiekermann, Wegener, Květoň, Marada, Schürmann et al., 2015). We assume the largest possible range of travel lengths, i.e., from very short trips limiting the attractiveness of the destination to half at the 15 or 30-minute travel times, gradually extending the length of the trip, ending with 12 hours of "half-life" values. We perform a series of simulations testing the scope of the impact of the population and infrastructure components on changes in accessibility for particular "half-life" values in each decade in each of the countries analyzed, in order to finally select the half-life for which the infrastructure component plays the greatest role in changing accessibility.

2.4 Data sources for components

The possibilities of comparative analyses between countries over a long period of time are related to new database possibilities, both regarding population data and network data. Historical population data comes from the EUROSTAT project supported by the Directorate-General for Regional and Urban Policy (European Commission Directorate-General for Regional and Urban Policy et al., 2013). These estimates are for European local administrative units (LAU) for the years 1961-2011 (January 1 of the first year of each decade), including, inter alia, EU Member States. For comparability, data from the National Censuses were recalculated for local administrative boundaries for 2011 and interpolated for the above-mentioned dates (European Commission Directorate-General for Regional and Urban Policy et al., 2013). For 2020, the data source at NUTS level was Eurostat and for the purposes of the paper, the NUTS 3 level of spatial resolution was utilized (Figure 1).

We combine dispersed data sources for individual countries to prepare a detailed analysis of the years of construction of individual sections of the road network. The focus was on the network of motorways, express roads and other dual carriageways, particularly those connecting regional centers at the NUTS3 level. The initial data source for the road network was the OpenStreetMap (OSM) database (Rosik et al., 2020), but it was subject to further processing. Four categories of OSM roads were taken into account: motorways, trunk roads, primary roads and secondary roads. Information regarding roads for specific years of opening mainly derives from websites and forums of road enthusiasts, such as Map of the construction status of highways and expressways (2024) or Highways and Expressways database (2024). Data collected were supplemented with archived press information from local newspapers and websites. Following Stelder (2016), we also used current and historical road atlases as an additional source for the database and we compared our database with the one created by Stelder et al. (2013). Nevertheless, due to the inconsistencies in Stelder's network (see also Salas-Olmedo et al., 2015) in our study we mainly relied on our own database (Figure 1).

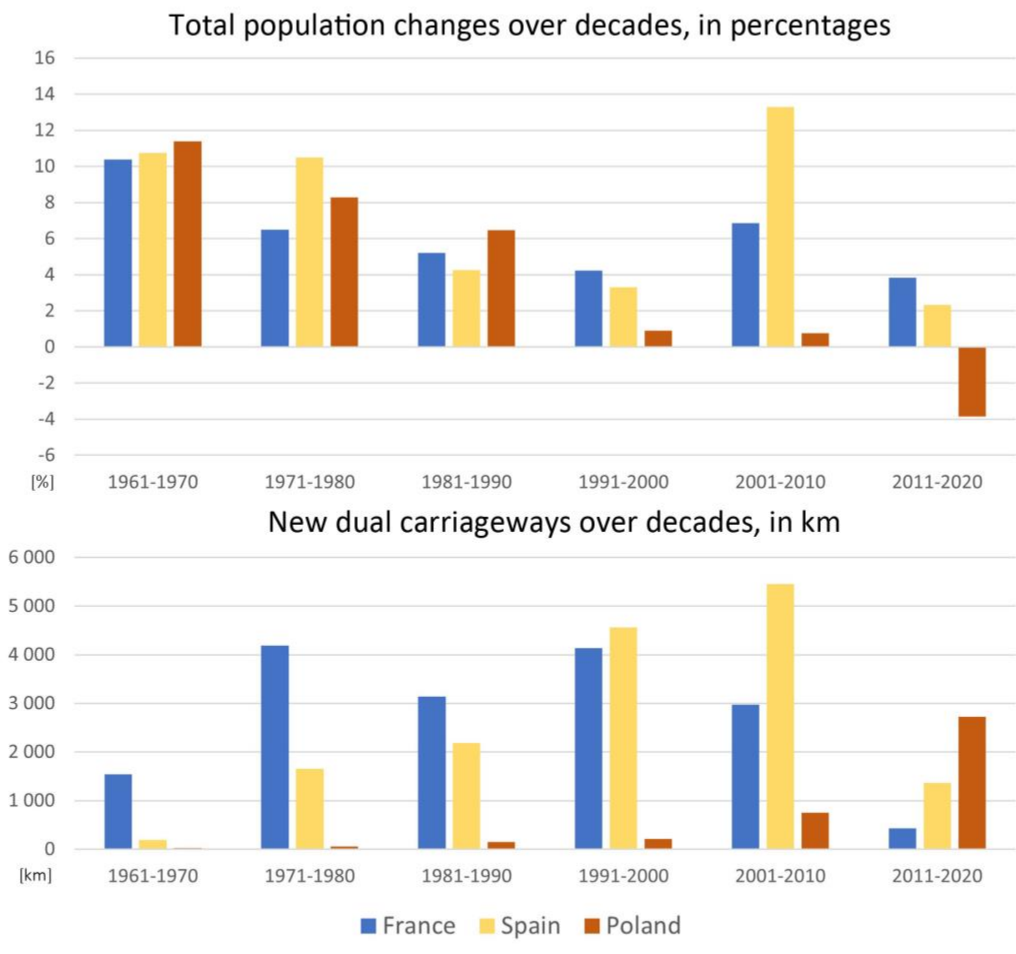

Figure 1. Changes in population and the length of dual carriageways in France, Spain, and Poland during the analyzed decades

We also looked at the Highway Code and speed limits on specific categories of road in each country (Table 1). We adopted constant speed limits for all road categories throughout the period of analysis. Changes in code speeds or congestion do not affect the impact of the infrastructure component, which, for the purposes of the evaluation, was to depend solely on investment activities. The travel times between road nodes, located a short distance from the city centers with the highest population in each transport zone were calculated using the shortest path algorithm, including the option of reaching all NUTS 3 Mediterranean islands in Spain (Balearic Islands) and France (Corsica) by ferry.

Table 1. Speeds of passenger vehicles adopted in the model by country and road category (km/h)

	Motorways*	Expressways**	Other dual carriageways and 2+1***	Single carriageway national roads**	Regional and local roads and connectors
France	130	110	100	90	70
Spain	120	120	100	90	70
Poland	130	120	105	90	70

* According to the speed in the code, except in Poland, where the code speed on motorways is 140 km/h. We assume the maximum speed on motorways in Poland is similar to that in France, i.e., 130 km/h.

** Code speeds.

*** Average speeds assigned to single-lane national roads and expressways.

2.5 Decomposition of accessibility in particular decades

Most authors address the topic of accessibility changes in the context of ex-post evaluation, although there are also exceptions of ex-ante evaluation, i.e., drawing scenarios of the impact of components on changes in accessibility in the future (as in Geurs & Ritsema van Eck, 2003). Evaluation is most often associated with programs for intensive expansion of transport infrastructure and these concern one decade (Lopez et al., 2008; Panagiotopoulos & Kaliampakos, 2021; Rosik et al., 2015), sometimes two decades (Holl, 2007; Stępniak & Rosik, 2018;), three decades (Geurs & Ritsema van Eck, 2003) or four decades (Kotavaara et al., 2011). However, there are also examples of longer time series, such as the analysis by Condeço-Melhorado et al. (2017) for five decades, Huang and Zong (2020) for 100 years in Southwest China and Axhausen et al. (2011) – for 150 years for Switzerland. In our paper, we engage in this rare case of analysis over a longer period of time, i.e., over six decades from 1960 to 2020. Thanks to this, we can analyze the variability over time of the impact of components on changes in accessibility in the long term. For this purpose, we use the coefficient of variation defined as the ratio of the standard deviation for six indices, corresponding to the six decades, of average annual percentage changes in accessibility (total change or as a result of the impact of a component) to the mean change in accessibility for a set of six decades (Formula 5):

$$CV_{c,v} = \frac{\sigma_{c,v}}{\Delta A_{c,v}} = \frac{\sqrt{\frac{\sum_{d=1}^{6}\left(\frac{A_{c,d+1}}{A_{c,d}}-1\right)^2}{6} - \left(\frac{\sum_{d=1}^{6}\left(\frac{A_{c,d+1}}{A_{c,d}}-1\right)}{6}\right)^2}}{\frac{\sum_{d=1}^{6}\left(\frac{A_{c,d+1}}{A_{c,d}}-1\right)}{6}} \quad (5)$$

where:

c – index of the country;

v – index of the component(s) considered as a variable in time (population or infrastructure);

d – index of the decade of v measurement, if $d = \frac{year-1950}{10}$;

$A_{c,d}$ – an aggregated potential measure in country c, if variable v as in decade d.

Indices of average annual changes in accessibility as a result of the impact of individual components make it possible to calculate the dominance (strength) of one of the components. For each of the six decades separately and jointly for the entire period under study, we examine three effects: (1) population (*ceteris paribus*), i.e., *ΔAP*; (2) infrastructure (*ceteris paribus*), i.e., *ΔAI*; (3) total, i.e., *ΔAD*. The average dynamics of accessibility caused by component(s) change and total change are calculated according to the formulas:

$$\Delta AP_{R,d_1,d_2} = \sqrt[\Delta d]{2 - \frac{A_{R,d_1,d_2}}{A_{R,d_2,d_2}}} - 1 \quad (6)$$

$$\Delta AI_{R,d_1,d_2} = \sqrt[\Delta d]{2 - \frac{A_{R,d_2,d_1}}{A_{R,d_2,d_2}}} - 1 \quad (7)$$

$$\Delta AD_{R,d_1,d_2} = \sqrt[\Delta d]{2 - \frac{A_{R,d_1,d_1}}{A_{R,d_2,d_2}}} - 1 \quad (8)$$

where:

$\Delta d = d_2 - d_1 = \frac{final\ year - initial\ year}{10}$ – time period under consideration, in decades;

d_1 – index of the decade of initial accessibility measurement;

d_2 – index of the decade of final accessibility measurement.

The total effect, ΔAD, is slightly different from the sum of two effects (population; ΔAP and infrastructure; ΔAI) because both effects in spatial terms can transform the geographical time-space (the differences are included in the OTHER column in Table 3).

2.6 Dimensions of the interplay of accessibility components, regional typologies

Three dimensions of the interplay of the impact of accessibility components on changes in accessibility are identified:

1. Dominance (of strength) of components – shows the scale of domination of the influence of one component over the other in relative terms, regardless of the direction of influence.
2. Combination of influence signs of components – four possible combinations depending on the "plus" or "minus" sign corresponding to the influence of each component on the change in accessibility.
3. Ratio of components (relative values) – shows the ratio of changes in the impact of the accessibility components.

Within the first of the proposed typologies, we focus on the dominance (of strength) of one component over the other (first dimension), which is a modified version of the index of the role of a given component (R_c) presented by Stępniak & Rosik (2018). We call the index the Coefficient of Dominance of Strength of components (*CS*) represented by Formula 9:

$$CS_{R,d_1,d_2} = \frac{|\Delta AD_{R,d_1,d_2} - \Delta AP_{R,d_1,d_2}| - |\Delta AD_{R,d_1,d_2} - \Delta AI_{R,d_1,d_2}|}{\max(|\Delta AD_{R,d_1,d_2} - \Delta AP_{R,d_1,d_2}|; |\Delta AD_{R,d_1,d_2} - \Delta AI_{R,d_1,d_2}|)} \quad (9)$$

where *ΔAD* is the average annual total change in accessibility in a given time period, and *ΔAP* and *ΔAI* are the average annual changes in accessibility resulting from the population component (with constant infrastructure values) and the infrastructure component (with constant population values), respectively. *CS* values range from -1, which indicates the dependence of the change in accessibility on the population component to +1 for the dominance of the infrastructure component in the change in accessibility. Values close to zero indicate that the influence of both components is balanced, with an *CS* of zero referring to a hypothetical total equality of both components.

The disadvantage of the typology used above is the lack of consideration of absolute difference or relative ratio of component dynamics when component changes act in different directions (have different signs), e.g., when the population component has a negative effect and the infrastructure component has a positive effect on accessibility changes. For this reason, we introduce two new indicators, i.e.,

(a) Coefficient of the absolute difference (*CD*) between infrastructure and population components (Formula 10). The most negative *CD* value indicates the largest advantage of change in accessibility resulting from population component over the improvement of access from infrastructure development. In turn, the most positive value indicates the greatest advantage of increase in accessibility resulting from infrastructure development over that from the positive population change or, most likely, the greatest sum of the effects of both infrastructure development and negative population change. Values close to zero indicate that the change in accessibility caused by both components is similar, with a *CD* of zero referring to equal dynamics caused by both components.

$$CD_{R,d_1,d_2} = \Delta AI_{R,d_1,d_2} - \Delta AP_{R,d_1,d_2} \tag{10}$$

(b) Coefficient of the relative ratio (*CR*) of components (Formula 11). *CR* indicates ratio (relative difference) of the dynamics of accessibility caused by change of both components, regardless of the scale of this dynamics. Unlike *CS*, *CR* captures the direction of *ΔAP* and *ΔAI*. Values of *CR* range from 0, which indicates the dependence on the exclusive favorable change in population component, through 0,5 (equality of positive impact of both components on accessibility increase) until 1 for the exclusive impact of infrastructural development. However, in opposition to *CS*, in case of negative impact of population component *CR* index is still growing towards 1,5, if positive effects of infrastructure development are counteracted by the unfavorable impact of population component, and further, when the latter becomes increasingly dominant over the infrastructure component, up to a value of 2, if the overall decrease in accessibility is due exclusively to the negative impact of population component.

$$CR_{R,d_1,d_2} = \frac{-\Delta AP_{R,d_1,d_2}}{|\Delta AI_{R,d_1,d_2}| + |\Delta AP_{R,d_1,d_2}|} \tag{11}$$

For all three typologies used in the paper, the indicators were calculated in both non-standardized (Formulas 9, 10, 11) and standardized terms (see Formulas 14, 15 and 16 in Appendix). A non-standardized approach was used in the cartographic presentation. However, the standardized approach was intended to enable the calculation of the CV, coefficient of variation, of all indexes for six decades. Temporal variability of indexes for six decades in the period 1960-2020 is calculated according to the Formula 12:

$$CV_{R,I} = \frac{\sigma Coef_R}{\overline{Coef_R}} = \frac{\sqrt{\frac{\sum_{d_1=1}^{6}\left(Coef_{R,d_1,d_1+1}\right)^2}{6} - \left(\frac{\sum_{d=1}^{6} Coef_{R,d_1,d_1+1}}{6}\right)^2}}{\frac{\sum_{d_1=1}^{6} Coef_{R,d_1,d_1+1}}{6}} \tag{12}$$

where:

$Coef$ – the considered standardized coefficient of the interplay of components in the region R or country c (CSS, CDS or CRS)

The typologies used differ from each other depending on the degree to which the three dimensions of the analysis of the impact of components on the change in accessibility are taken into account, in accordance with Table 2.

Table 2. Dimensions and indices of the interplay of accessibility components

		Dimensions		
		Dominance (of strength) of components	Combination of influence signs of components	Ratio of components
Indices	CS (Dominance of Strength)	v	x (modulus)	v (relative values)
	CD (Absolute Difference)	v	v	x (absolute values)
	CR (Relative Ratio)	v	v	v (relative values)

Weighted means of *CS*, *CD* and *CR* coefficients in countries are calculated according to Formula 13:

$$M_{c,I,d_1,d_2} = \frac{\sum_{r=1}^{n}\left(P_{r,d_2} \times I_{r,d_1,d_2}\right)}{\sum_{r=1}^{n} P_{r,d_2}} \qquad (13)$$

where:
I – index of the coefficient (CS, CD or CR);
n – number of the regions in the country c.

3 Results

3.1 Distance decay. Parameter selection

The number of simulations (3 countries x 6 decades x 12 selected half-lives) of the impact of the infrastructure component on the change in accessibility *ΔAI* indicate that for the decades with the highest average annual increase in accessibility, the greatest effects of the infrastructure component occur in France during the 1970s for a half-life of 60 or 90 minutes (increases of 1.00% or 1.05% respectively), in Spain during the 1990s for a half-life of 90 minutes (increase of 1.16%) and in Poland during the 2010s for half-lives of 45 and 60 minutes (increases of 1.13% and 1.04%). Similar half-life values also dominate in other decades. Therefore, basically regardless of the decade and the intensification of the investment process, the maximization of accessibility changes as a result of infrastructure expansion for the three countries analyzed takes place for half-lives between 45 and 90 minutes. Therefore, the choice of the travel length for further analyses was a half-life of 60 minutes as the most representative one. It is also a half-life corresponding to simulations of accessibility changes for long trips, already tested by Stępniak and Rosik (2018).

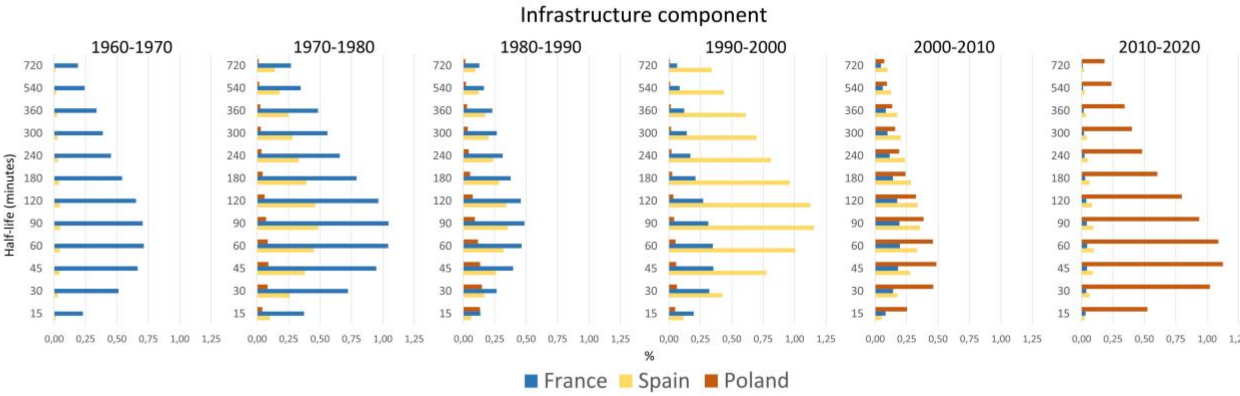

Figure 2. Infrastructure-driven percentage changes in annual potential accessibility *ΔAI* by country, decade and trip length; net effect of infrastructure investments if the population at the end of the decade remains unchanged

Analogous simulations for the impact of the population component *ΔAP* (Figure 3) indicate that the length of the trip does not have a decisive role on the scale of changes in accessibility, perhaps with the exception of Spain where the impact of the population component is usually particularly high for short trips, while in France, on the other hand, the impact changes in the opposite situation.

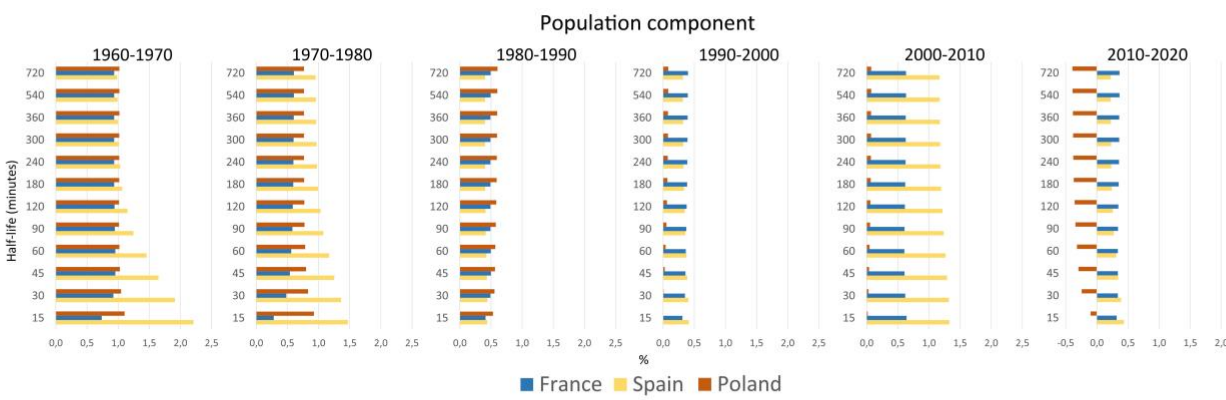

Figure 3. Population-driven percentage changes in annual potential accessibility *ΔAP* by country, decade and trip length; net effect of population change if the infrastructure at the end of the decade remains unchanged

3.2 Variation of component effects in time and space. Typology of regions

As already mentioned, each country had periods of faster growth in accessibility driven by large investment programs. However, there were also periods of slower progress in the overall increase in accessibility, as in France and Spain in the 2010s or in Poland in the 1990s. Throughout the period 1960-2020, interdecadal variations in accessibility growth were similar in all countries. Small differences in standardized *CV* coefficients were observed, ranging from 30% in Spain to 33% in France and Poland.

However, there are much greater differences between countries in the variability of the impact of individual components on changes in accessibility, i.e., variability of ΔAI and ΔAP. In Poland, in conditions of strong population growth, there was no significant development of infrastructure until the period of systemic change at the turn of the 1980s and 1990s. In the last three decades, in conditions of growing depopulation, there was also a big infrastructure push which gained importance in the decades which followed. Therefore, the variability with time of the impact of each component on changes in accessibility in Poland is the highest for both components. In Poland, the standardized coefficient of variation for the infrastructure component is as high as 59%, and for the population component, 68%. Meanwhile, in Spain and France, the variability of the impact of both components with time is lower than in Poland, and the standardized variability with time of the impact of the infrastructure component on accessibility is correspondingly higher in these countries (*CV* 44% and 41%, respectively) than the variability with time of the impact of the population component (CV 39% and 22%, respectively) (Table 3).

Table 3. Variation with time of the impact of population and infrastructure components on changes in accessibility and the variability of the interplay of components

	Components and ΔAD								Interplay of components					
France	**ΔAI**	**ΔAI stand.**	**ΔAP**	**ΔAP stand.**	**ΔOther**	**ΔOther stand.**	**ΔAD**	**ΔAD stand.**	**CS**	**CSS**	**CD**	**CDS**	**CR**	**CRS**
1960-1970	0,69%	1,02%	0,92%	1,24%	-0,11%	0,21%	1,50%	1,82%	-27,26%	36,37%	-0,22%	1,10%	43,03%	21,51%
1970-1980	1,00%	1,32%	0,55%	0,87%	-0,15%	0,18%	1,40%	1,72%	52,07%	76,04%	0,45%	1,77%	64,54%	32,27%
1980-1990	0,45%	0,78%	0,49%	0,81%	-0,04%	0,29%	0,90%	1,23%	-6,85%	46,58%	-0,03%	1,29%	48,33%	24,17%
1990-2000	0,34%	0,67%	0,36%	0,68%	-0,06%	0,26%	0,64%	0,97%	-5,18%	47,41%	-0,02%	1,31%	48,89%	24,45%
2000-2010	0,19%	0,52%	0,59%	0,91%	-0,06%	0,27%	0,73%	1,05%	-73,60%	13,20%	-0,39%	0,93%	24,81%	12,41%
2010-2020	0,04%	0,37%	0,33%	0,66%	-0,04%	0,29%	0,34%	0,66%	-98,65%	0,68%	-0,29%	1,03%	11,64%	5,82%
Mean	0,45%	0,78%	0,54%	0,86%	-0,08%	0,25%	0,92%	1,24%	-26,58%	36,71%	-0,08%	1,24%	40,21%	20,10%
StdDev	0,32%	0,32%	0,19%	0,19%	0,04%	0,04%	0,41%	0,41%	49,06%	24,53%	0,27%	0,27%	17,29%	8,65%
CV	**-**	**40,58%**	**-**	**22,38%**	**-**	**16,77%**	**-**	**33,12%**	**-**	**66,81%**	**-**	**22,13%**	-	**43,01%**
1960-2020	0,38%	0,70%	0,43%	0,75%	-0,17%	0,15%	0,63%	0,96%	-18,85%	40,58%	-0,05%	1,27%	46,84%	23,42%
Spain	**ΔAI**	**ΔAI stand.**	**ΔAp**	**ΔAp stand.**	**ΔOther**	**ΔOther stand.**	**ΔAD**	**ΔAD stand.**	**CS**	**CSS**	**CD**	**CDS**	**CR**	**CRS**
1960-1970	0,05%	0,37%	1,37%	1,69%	0,28%	0,61%	1,70%	2,02%	-78,77%	10,62%	-1,32%	0,00%	3,31%	1,65%
1970-1980	0,44%	0,77%	1,11%	1,44%	0,08%	0,40%	1,63%	1,96%	-55,07%	22,46%	-0,67%	0,65%	28,42%	14,21%
1980-1990	0,32%	0,64%	0,42%	0,74%	-0,02%	0,30%	0,71%	1,04%	-25,56%	37,22%	-0,10%	1,22%	43,03%	21,51%
1990-2000	0,96%	1,29%	0,37%	0,69%	-0,02%	0,30%	1,31%	1,63%	62,47%	81,24%	0,60%	1,92%	72,38%	36,19%
2000-2010	0,33%	0,65%	1,20%	1,52%	0,01%	0,33%	1,54%	1,86%	-71,02%	14,49%	-0,87%	0,45%	21,46%	10,73%
2010-2020	0,10%	0,42%	0,31%	0,63%	0,07%	0,40%	0,47%	0,80%	-55,02%	22,49%	-0,21%	1,11%	24,09%	12,04%
Mean	0,37%	0,69%	0,79%	1,12%	0,07%	0,39%	1,23%	1,55%	-37,16%	31,42%	-0,43%	0,89%	32,11%	16,06%
StdDev	0,30%	0,30%	0,44%	0,44%	0,11%	0,11%	0,47%	0,47%	47,57%	23,79%	0,61%	0,61%	21,45%	10,73%
CV	**-**	**43,50%**	**-**	**39,20%**	**-**	**27,07%**	**-**	**30,28%**	**-**	**75,70%**	**-**	**68,77%**	-	**66,80%**
1960-2020	0,31%	0,63%	0,58%	0,90%	-0,12%	0,20%	0,76%	1,08%	-56,34%	21,83%	-0,27%	1,05%	34,79%	17,39%
Poland	**ΔAI**	**ΔAI stand.**	**ΔAP**	**ΔAP stand.**	**ΔOther**	**ΔOther stand.**	**ΔAD**	**ΔAD stand.**	**CS**	**CSS**	**CD**	**CDS**	**CR**	**CRS**
1960-1970	0,00%	0,33%	0,98%	1,30%	-0,01%	0,32%	0,97%	1,30%	-99,40%	0,30%	-0,98%	0,35%	0,02%	0,01%
1970-1980	0,08%	0,41%	0,76%	1,08%	0,00%	0,33%	0,85%	1,17%	-88,19%	5,90%	-0,67%	0,65%	9,96%	4,98%
1980-1990	0,12%	0,44%	0,56%	0,88%	-0,05%	0,28%	0,62%	0,95%	-86,39%	6,80%	-0,44%	0,88%	17,22%	8,61%
1990-2000	0,05%	0,38%	0,04%	0,36%	-0,05%	0,27%	0,04%	0,36%	-96,81%	1,60%	0,01%	1,33%	57,01%	28,51%
2000-2010	0,45%	0,78%	0,05%	0,37%	-0,04%	0,29%	0,46%	0,79%	97,57%	98,78%	0,41%	1,73%	90,89%	45,45%
2010-2020	1,04%	1,36%	-0,33%	0,00%	0,11%	0,44%	0,83%	1,15%	80,22%	90,11%	1,36%	2,69%	123,83%	61,91%
Mean	0,29%	0,62%	0,34%	0,67%	0,00%	0,32%	0,63%	0,95%	-32,17%	33,92%	-0,05%	1,27%	49,82%	24,91%
StdDev	0,37%	0,37%	0,46%	0,46%	0,06%	0,06%	0,31%	0,31%	85,87%	42,93%	0,78%	0,78%	45,36%	22,68%
CV	**-**	**59,37%**	**-**	**68,36%**	**-**	**17,32%**	**-**	**32,62%**	**-**	**126,59%**	**-**	**61,09%**	-	**91,05%**
1960-2020	0,26%	0,59%	0,31%	0,63%	-0,09%	0,23%	0,48%	0,81%	-19,75%	40,12%	-0,05%	1,28%	46,05%	23,02%

Periods of very high impact of the development of road infrastructure on improving accessibility (average annual impact per decade close or above 1%) are limited to one decade at 20-year intervals in the countries examined, i.e., in the 1970s in France, the 1990s in Spain and the 2010s in Poland. In the remaining decades, much smaller effects of the impact of improvements in infrastructure on the increase in potential accessibility are usually recorded, with the annual average for the entire period 1960-2020 being 0.31% in Spain, 0.26% in Poland and 0.38% in France, respectively. In France and Spain, the decade of rapid development of road infrastructure is the only one for which the *CS* index>0. By contrast, in Poland, in the big push decade of 2010-2020 and also in the previous decade, i.e., in the years 2000-2010, there is a domination of the infrastructure component over the population one, but with very low values of the population component, primarily due to the stabilization of the population in this country.

In turn, a very high, even above 1%, average annual impact of the population component on the change in accessibility, concerned the years 1960-1980 and 2000-2010 in Spain (in this country it is also the strongest for the entire period). In France, the impact of the population component on the change in accessibility is more balanced, generally decreasing over time, but with no major fluctuations between decades as in Spain or Poland. A very strong dominance (CS>80%) of the population component over the infrastructure component occurs in France in the most recent decade and in Poland in the first three decades of the period analyzed. Each time this is related to the very slow development of road infrastructure in these countries.

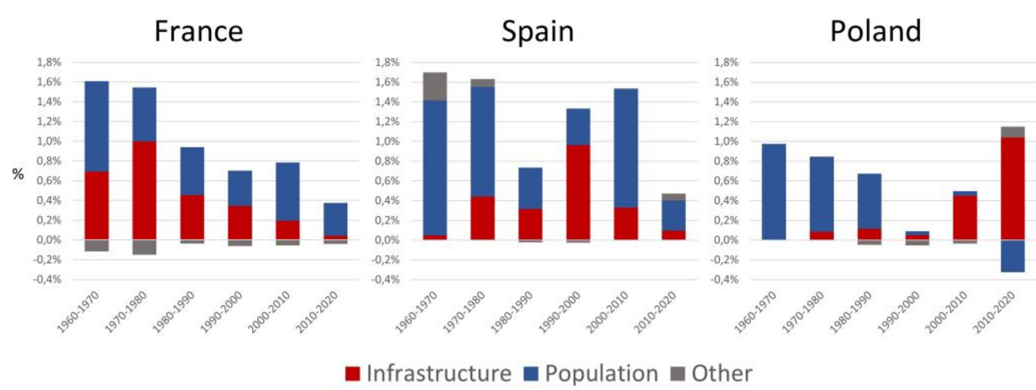

Figure 4. Decomposition of potential road accessibility growth in France, Spain and Poland 1960-2020

A detailed analysis of the decomposition of the increase in accessibility indicates that we are dealing with a special situation in Poland in the years 2010-2020, where there is a very strong impact of infrastructure development with a negative impact of population change. This is the only case nationwide for which the impact of both components has an opposite sign (Figure 4). At a lower level of aggregation, i.e., at the NUTS3 level, a similar situation also occurs, for example, in north-western Spain (see also Nogues & Gonzalez-Gonzales, 2021), with the note that while, for example, in the 1960s (then also affecting Extremadura and part of Andalusia), the negative impact of the population component prevailed over the positive infrastructural component (i.e., CS<0), while in the 1990s, the negative impact of the population component is lower than the positive impact of the expansion of road infrastructure (therefore CS>0). A similar case of a sudden change in the impact of components is noticeable in north-eastern Poland (Podlaskie Voivodeship), which has long lagged behind in terms of access to highways and until 2000 the positive impact of the population component dominated, only to give way to the infrastructure component in the 21st century, with an increasingly strong negative impact of the population component (Figure 5).

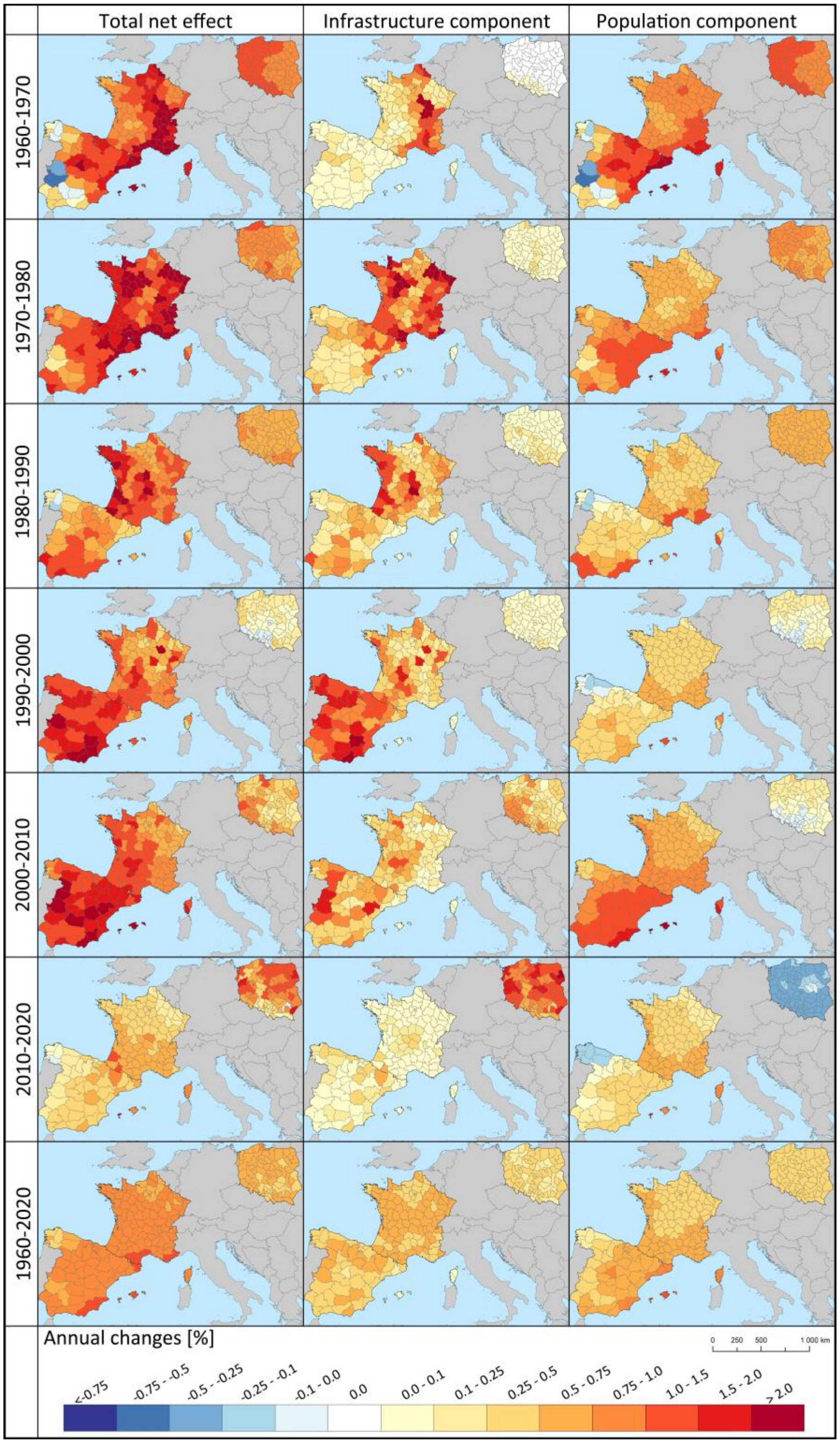

Figure 5. Changes in accessibility level, both total and as a result of the infrastructure and population components by decade and over six decades (half-life = 60 minutes)

The use of a typology based on ***CS*** shows the dominance of strength of components, indicating the overall impact of transport and spatial policies. In terms of the entire period of 1960-2020 (Figure 6), this typology shows, compared to other typologies, fewer regions with a balanced impact of both components and a strong impact of the infrastructure component, especially in peripheral areas, including depopulation areas.

The use of **absolute difference (*CD*)** highlights periods of intensive infrastructure development (big push decades) expressed by high indicators of domination of the infrastructure component in most of the country (e.g., in Spain in the 1990s), but also by a stronger emphasis on the effects of individual infrastructure projects, which is evident in France in the first four decades of the period under study. However, over the entire period, this type flattens the results the most, resulting in low values of variability and showing a balanced picture of the impact of components for most regions (Figure 8).

The use of **relative ratio (*CR*)** helps to highlight the interregional differences in the impact of both components in periods with different signs of their impact, both in periods of intensive infrastructure development, as in Poland in the 2010s, and in periods of relatively low changes in both components, e.g., in Poland in the 1990s (Figure 6 and 7).

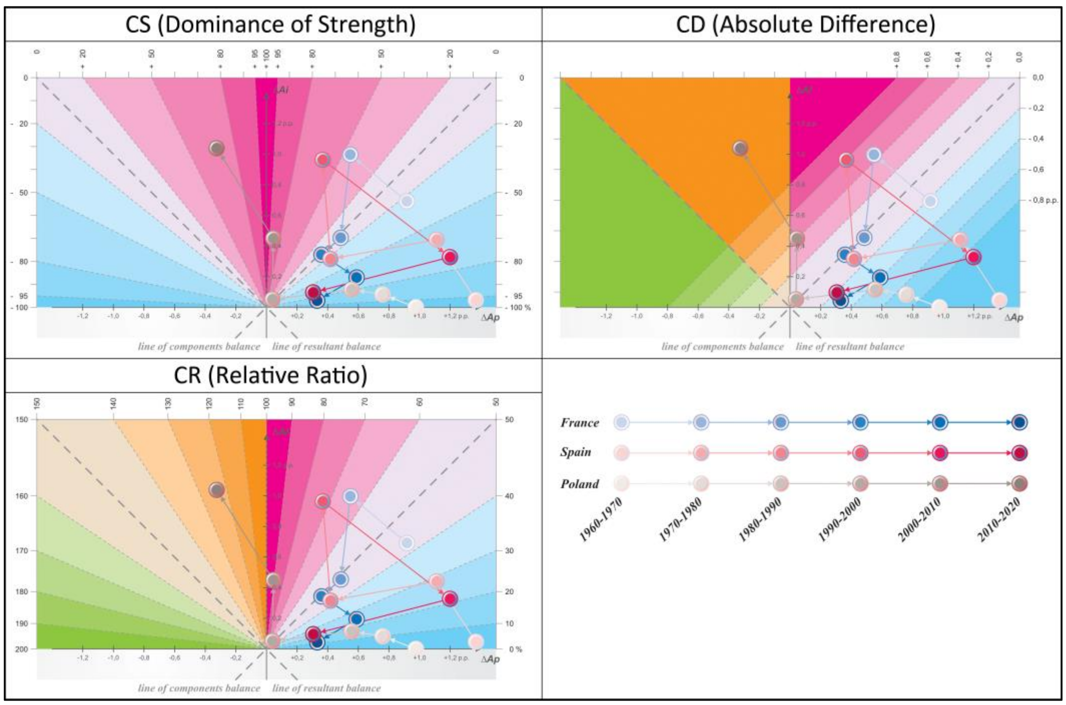

Figure 6. Three indices of the interplay of accessibility components at the national level (France, Spain and Poland; 1960-2020)

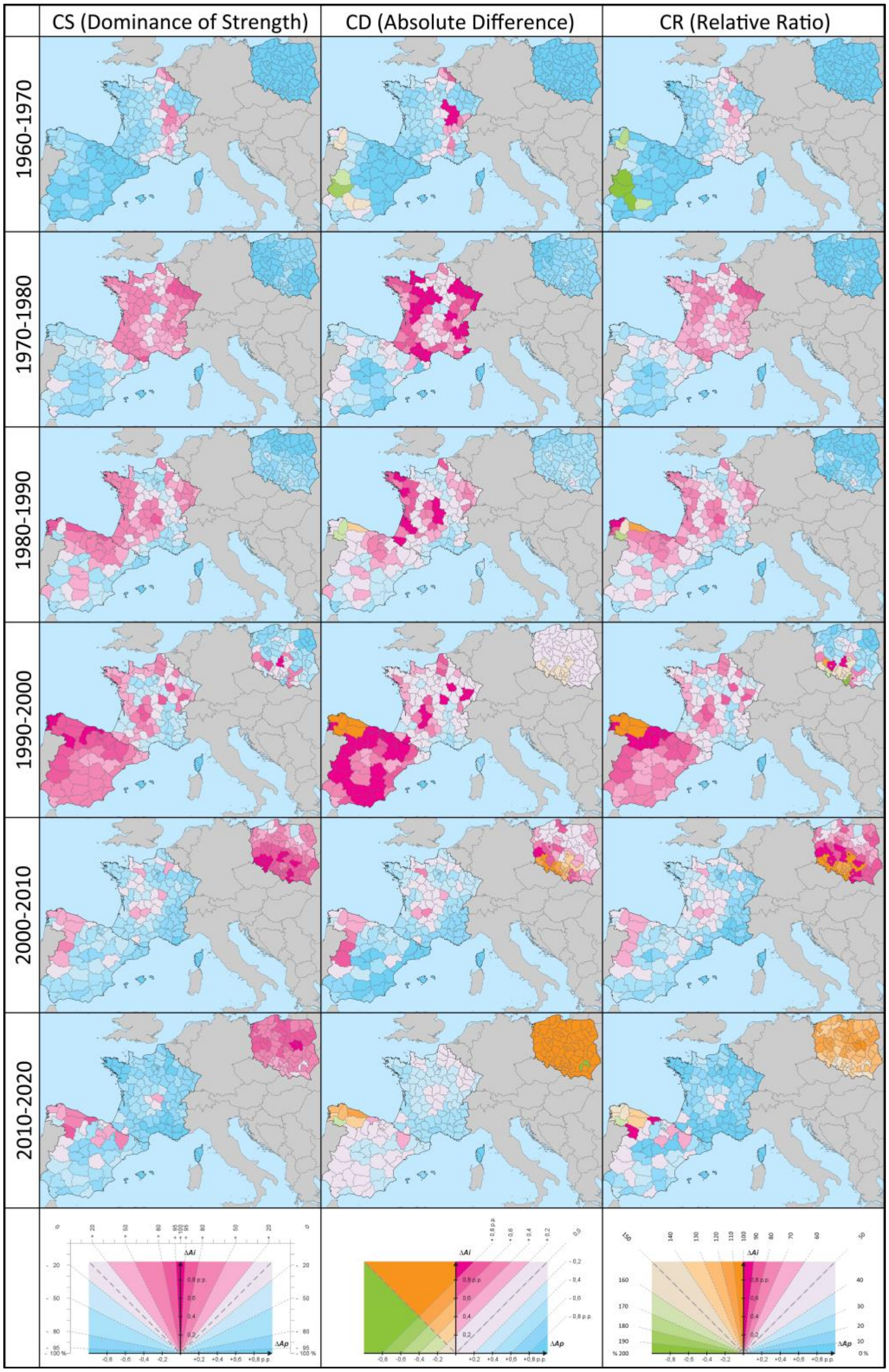

Figure 7. Regional typologies based on three indices of the interplay of accessibility components

For the entire period 1960-2020, the western and north-western areas of Spain cited, individual border regions in Poland, as well as the Franco-German and Franco-Belgian borders and the Centre-Val de Loire areas in France are the areas where the infrastructure component predominates. In most of the territory of the countries examined, however, there has been a predominance of the population component over the past six decades or the situation is more or less balanced. This means that, in particular for *CD* (Absolute Difference) and *CR* (Relative Ratio) indices, in most of the studied area there is no clear advantage of any of the components in the long term (Figure 8).

Poland has a particularly high variability of the interplay of components (Table 3 and Figure 8) in the six decades studied for CS and CR indices. In Spain, CV is higher than in France and Poland for CD index, which is also due to high variability in Catalonia and Madrid, where intensive infrastructure development took place in periods other than those with population growth. In turn, in the case of Andalusia, the results vary significantly depending on the typology adopted in a similar manner to the Côte d'Azur or Brittany in France. In Andalusia, this is the result of high variability in population growth in this area, initially depopulating and then gaining in population during the tourism boom in the early 21st century.

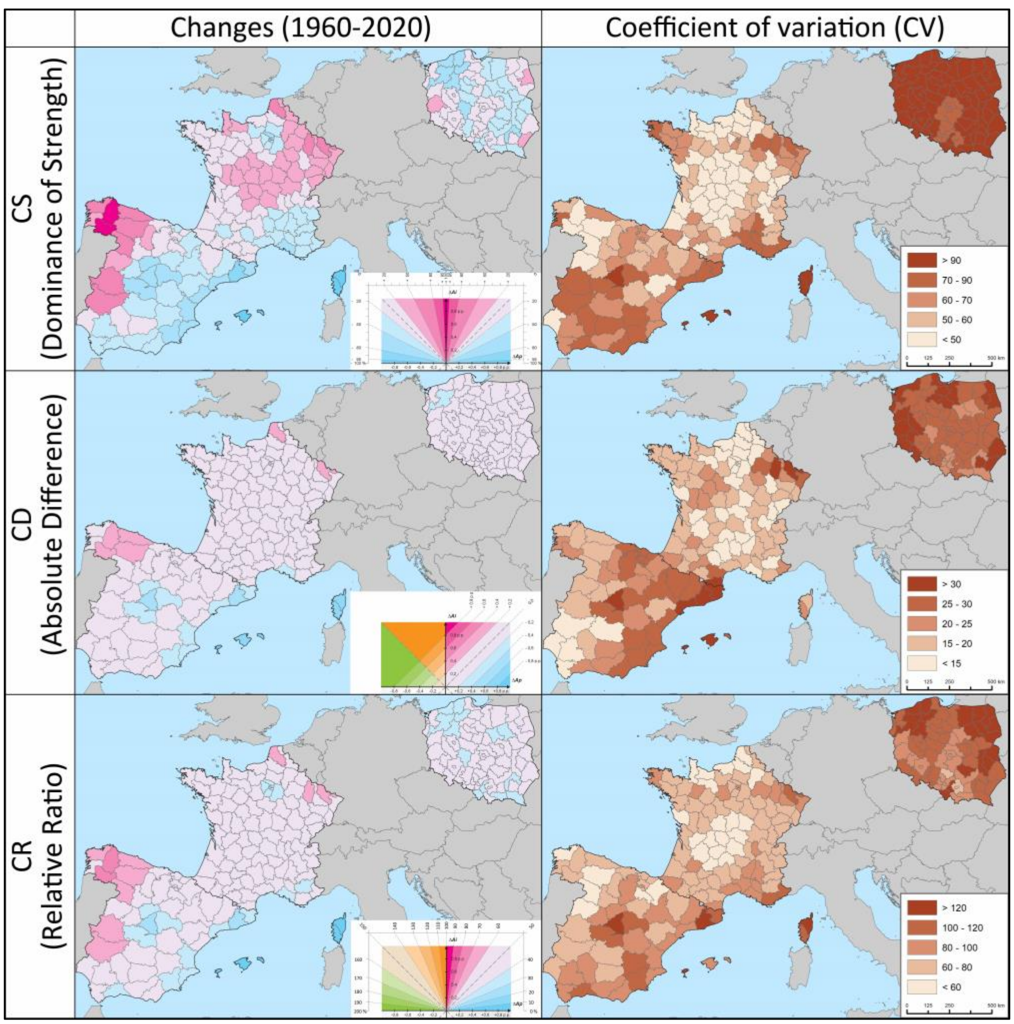

Figure 8. Changes (1960-2020) and variability (CV) of three indices of the interplay of accessibility components

4 Conclusions and discussion

Our results show that there is great variability in the interplay between accessibility components (strength, difference and ratio) at the regional NUTS3 level. The main cause of this variability is change at the national level. These changes include long-lasting rapid infrastructure development throughout the country or periods of depopulation or population growth in a given country. Particularly high variability occurs in peripheral areas, which are usually depopulated and have significant deficiencies in transport connections with central areas. By contrast, areas that are attractive to live in and easily accessible, where the population is consistently increasing, such as the Côte d'Azur in France, as well as Madrid and Catalonia in Spain, show a strong dominance of the population component throughout the period but they are also subject to high variability of the indices (Figure 8). This is due particularly to the fact that during single decades of intensive infrastructure development at the national level, the infrastructure component dominates in these areas.

In Central and Eastern Europe, e.g., in Poland, where infrastructure delays were of a systemic nature and concerned the entire country, we can expect another decade (i.e., until 2030) of domination of the infrastructure component (Rosik et al., 2018). It is likely, that this will be accompanied by an increasingly strong negative impact of the population component. Assuming no intensification of immigration processes and a gradual decline in infrastructure development, this may result in decreasing accessibility in large areas in the following decades. Previously, declining levels of accessibility occurred in Extremadura in Spain in the 1960s and, to a lesser extent, in Silesia in Poland in the 1990s. In the near future, the dominance of the infrastructure component may still occur at the NUTS-3 level in areas lagging behind in infrastructure development, for example, in Central Pomerania in north-western Poland, where to date it is the population component that has dominated; this would be a unique exception among peripheral regions. The dominance of one component over the other in similar regions will depend on the strength of the infrastructure development process, as well as the extent of further depopulation in peripheral areas.

One key aspect of expanding the model presented in this paper is to broaden the regional typology to include a potential negative impact on accessibility related to the transportation component, in line with existing literature on vulnerability and resilience (Jenelius et al., 2006; Mattsson & Jenelius, 2015; Wiśniewski et al., 2020). A negative impact on local accessibility may be related to limiting capacity, inter alia introducing bus lanes. In turn, the degradation of infrastructure may be temporary, e.g., as a result of the modernization/renovation of a bridge, or permanent, e.g., the liquidation of a road connection as a result of the creation of artificial reservoirs or due to warfare. The extension of travel times may also occur as a result of taking into account increased congestion in the model (agglomeration effects), e.g., as a result of a gradual increase in population density in metropolitan areas over the decades in the absence of major infrastructure activities.

Further research is also recommended on the role of travel length on the impact of both components. In particularly, this refers to countries with different settlement systems and stages of the investment process, e.g., for the dominance of investments in central or peripheral regions. In the latter, the relationship between the investment process and depopulation processes is interesting, also in the context of the sequentiality of actions and the effects, e.g., of stopping migration and flushing out resources (as in Kotavaara et al., 2011). It is important to examine how different spatial factors, such as population changes in the center-periphery pattern, impact accessibility.

The added value of this paper is the separation of the "third" component in the form of OTHER in Table 3. The value of OTHER probably results from the spatial mismatch between the direction and scale of changes in the distribution of masses, i.e., population (Jażdżewska, 2006), and the direction and scale of transformations of geographical time-space by road transport systems (Moser et al., 2023; Spiekermann & Wegener, 1994). The topic requires further research using centrographic measures. When population increases or travel times decrease uniformly across the country over a given period, it results in a proportional change in potential. In practice, however, any such modification occurs irregularly and involves a corresponding change in the spatial structure of mass distribution and speed across different sections of the transport network. When the change in the spatial allocation of mass leads to a reduction in the average distance between its units, or when sections of the network are upgraded, reducing the distance decay between relatively large masses, a positive synergy effect is created, reflected in a positive OTHER value. The two spatial structures behind the potential components then become better matched to each other, making the potential higher than what would result from the sum of the change in mass and the average generalized travel cost. Conversely, when a change in the distribution of mass leads to an increase in the average travel cost between its units, or when this cost is reduced on relatively less significant sections of the network (see also Jenelius et al., 2006), negative synergies are created and the OTHER component acquires a value below zero. This third component is thus related to the distortion of topological relations in geographical timespace that arises with any disproportionate change in either timespace or population distribution. Although apparently, it has a relatively small impact on the final value of the potential, it is nonetheless meaningful as it provides empirical evidence that overall improvements in accessibility can be achieved not only by increasing the parameters of the transport network or the total population available in a given area. It can be also achieved by appropriately prioritizing investments and optimizing the distribution of the population. The OTHER component may also require some further work on the first indicator (*CS*) we proposed in this paper, because this index is very sensitive to simultaneous low changes in infrastructure and population components and high changes of OTHER, such as in Poland in the 1990s.

Moreover, it is recommended to test the impact of other variables within both components, e.g., GDP, jobs or services in the land-use component. Additionally, changes in code speeds, model assumptions regarding self-potential or penalties, and high-speed rail, air or multimodal long-distance accessibility (Beria et al., 2017; Monzon et al., 2019; Randák et al., 2021) should also be considered in the transport component. The speed values assumed in the paper do not account for the fact that even free-flow speeds are typically below the speed limits, nor do they consider potential lower speed limits in certain areas, particularly urban ones. Consequently, the travel times derived from the model might be slightly shorter than those achievable in reality. Therefore, each new road segment introduced over time in the model might overestimate the contribution of the infrastructure component.

Another methodological improvement and simultaneous reduction of the limitations of the model that was applied is to increase spatial resolution to the LAU level, similar to the approach in Spiekermann, Wegener, Květoň, Marada, Schurmann et al. (2015) and Spiekermann, Wegener, Květoň, Mattern et al. (2015). This would better estimate accessibility changes within NUTS units and between neighboring regions. It would also improve the assessment of accessibility changes within internal peripheries, where depopulation processes and infrastructure access limitations may be more intense than in the centers of NUTS3 units. Related to this is the problem of self-potential. For instance, most of the development processes within urban agglomerations, such as the suburbanization of the population and the corresponding transport infrastructure development benefiting mainly the regional population, are not covered in the model due to the size of NUTS 3 regions. However, these processes have tremendous impacts on accessibility and its decomposition. Such problems with self-potential are much smaller or even negligible when modeling at the LAU level (Stępniak & Jacobs-Crisioni, 2017).

Acknowledgments

This research was funded by the Polish National Science Centre allocated on the basis of the decisions no. 2018/29/B/HS4/01999 (concept and methodology) and 2020/37/B/HS4/00544 (calculating distances). The views expressed here are purely those of the authors and may not, under any circumstances, be regarded as an official position of the European Commission.

Author contribution

The authors confirm their contribution to the paper as follows: study conception and design: P. Rosik, M. Stępniak, M. Mazur; data collection: S. Goliszek, P. Duma, M. Mazur; visualization: P. Duma, M. Mazur; analysis and interpretation of results: P. Rosik, M. Mazur, T. Komornicki, P. Churski; draft manuscript preparation: P. Rosik, M. Mazur. All authors reviewed the results and approved the final version of the manuscript.

Appendices

Appendices available as supplemental files at https://doi.org/10.5198/jtlu.2025.2508.

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