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Going Big in a Small Country: Fifty Years of Motorways in Portugal

Crescer num País Pequeno: Cinquenta Anos de Autoestradas em Portugal

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Abstract

Portugal's motorway network experienced significant transformation in a relatively short period. Until the mid-1980s, the network counted less than 200 kilometers, reaching more than 3 000 kilometers in the end of this decade of the 21st century. As a result of this strong investment, the country now has one of the largest and densest motorway networks in the European Union. This paper describes the methodology developed for the construction of a longitudinal spatial database covering 50 years of road improvements in mainland Portugal using the Geographic Information Systems environment technology. Besides containing information for different road networks, the database also includes administrative, demographic, and socioeconomic information for Portugal's mainland municipalities. Using the new database developed by the authors, the paper analyzes the evolution of the motorway network and the road-based accessibility to population and jobs over the period from 1971 to 2020. The new database is publicly available to other researchers and will, hopefully, be used in future studies on the socioeconomic impacts of road investments in Portugal, for example, to understand how improved road accessibility contributed to regional economic development or regional cohesion.

Keywords: Motorways; Road Accessibility; Portugal; Geographic Information Systems.

JEL Codes: R40; R41; R42

Resumo

A rede de autoestradas em Portugal sofreu uma transformação significativa num período relativamente reduzido. Até meados dos anos 80, a rede de autoestradas atingia menos de 200 quilómetros, em contraste com os mais de 3 000 quilómetros de extensão no final desta década do século XXI. Como resultado deste forte investimento, o país passou a dispor de uma das maiores e mais densas redes de autoestradas da União Europeia. Este artigo descreve assim, a metodologia desenvolvida para a construção de uma base de dados longitudinal, abrangendo 50 anos de melhorias contínuas ao nível rodoviário em Portugal Continental, recorrendo aos Sistemas de Informação Geográfica. Além da informação relacionada com as diferentes infraestruturas rodoviárias, a base de dados inclui também informação administrativa, demográfica e socioeconómica dos diversos municípios de Portugal Continental. Com esta nova base de dados desenvolvida, o artigo analisa a evolução da rede de autoestradas, assim como, a acessibilidade rodoviária à população e empregos no período entre 1971 e 2020. Esta nova fonte de informação está disponível ao público, assim como, investigadores que pretendam aceder, possibilitando estudos futuros sobre os impactos socioeconómicos dos investimentos rodoviários em Portugal, como exemplo, a melhoria da acessibilidade rodoviária no desenvolvimento económico e coesão regional.

Palavras-chave: Autoestradas; Acessibilidade Rodoviária; Portugal; Sistemas de Informação Geográfica.

Códigos JEL: R40; R41; R42

1. INTRODUCTION

Motorways in Portugal were almost non-existent during most of the 20th century. Until the mid-1980s, the motorway network counted less than 200 kilometers and was essentially limited to parts of the suburban areas of the two metropolitan areas of Lisbon and Porto. However, after joining the now European Union (EU) in 1986, the country gained access to European regional development funding, which was, in part, allocated to improving roads and building motorways. The contribution of European funds to the total investment in infrastructure, of which transport represented more than 50% of total investment, varied across the different financial frameworks: it accounted for 38% of total investment in the QCA I (1989-93), 60% in the QCA II (1994-99), 57% in the QCA III (2000-06), and 64% in the QREN (2007-13) according to Pereira (2013). Referring data from Pereira and Pereira (2016), in the period between 1980 and 2011, road investment represented about 29% of total investment in infrastructure (four times larger than the investment in railways), while motorways represented about 7% of total investment in infrastructure. The share of the investment effort in motorways increased over time, from 2.6% of total investment in infrastructure in the 1980s to 6.8% in the 1990s and 11.7% in the 2000s.

The motorway network increased from only 75 km in 1971 to about 3 164 km in 2020, which corresponds to an annual average growth rate of 7.9% over the entire period. The periods between 1991-2001 and 2001-2011 saw the largest construction of motorways, 1 114 km and 1 213 km, respectively. The network was essentially completed in 2013, with only minor changes taking place since then (e.g., some road connections to motorways and short sections of some motorway corridors). As a result of this strong investment, the country now has one of the largest and densest motorway networks in the EU. According to Eurostat data for 2020, Portugal has the fifth largest motorway network in absolute terms in the EU: only the much larger countries of Spain, Germany, France, and Italy have a larger motorway network than Portugal. If we consider the total length of motorways in relation to GDP, population, and area, Portugal ranks second, third, and fifth, respectively.

This paper has two main objectives. The first objective is to describe the construction of the longitudinal spatial database, named "TiTuSS Transport Database", for mainland Portugal's road network between 1971 and 2020 at ten-year intervals. The database is available in the cloud-based communal repository Mendeley Data and published as Afonso et al. (2023)[1]; see Appendix A for the list of variables. To obtain an internally consistent georeferenced longitudinal database, it was necessary to perform several validation tests for the integrity of the different road networks, as well as multiple quality control procedures. The paper can thus be seen as an extended manual supporting future uses of the resulting database. The second objective is to analyze how patterns of road accessibility have changed across municipalities over this 50-year period.

The database can be used to study a wide range of economic effects of roads, particularly of motorways, on the spatial economy. Improvements to transport infrastructure reduce transport costs and improve accessibility to input (i.e., suppliers, labour, etc.) and output markets, producing several impacts on the economy. These effects include, among other factors, the expansion and integration of wider markets, leading to productivity gains from improved labour supply and specialization; higher efficiency through scale economies and economic restructuring due to firm entry and exit resulting from stronger competition; and other productivity effects from spatial agglomeration economies. There are several review studies of the economic effects of transport infrastructure (e.g., Boarnet, 1997; Melo et al., 2013; Melo, 2021). The reduction in transport costs and improved accessibility can also influence the distribution of people and jobs both between and within regions, which in turn affects regional cohesion.

Importantly, the literature suggests that motorways contribute to the growth of local population and employment (e.g., Duranton and Turner, 2012; Percoco, 2016), the shifting population from central cities to their suburbs (e.g., Baum-Snow, 2007a; Baum-Snow, 2007b; Garcia-López, 2012; Garcia-López et al., 2015), and urban sprawl (e.g., Deng et al., 2008; Müller et al., 2010; Oueslati et al., 2015; Ahrens and Lyons, 2019; Garcia-López, 2019; Pratama et al., 2022). Our database already contributed to providing new evidence for Portugal on the role of motorways on local population growth and suburbanisation (e.g., Rocha et al., 2023) and local economic activity (e.g., Rocha et al., 2024), and we hope it can foster further research.

The paper is organized as follows. Section 2 provides an overview of the methodology adopted and of the sources of the road network data used. Section 3 describes the processes underlying the construction of the longitudinal spatial database, including the validation of the quality of the road networks (i.e., motorways, expressways, as well as national, regional, and municipal roads) in each period and their harmonization across the different periods. Section 4 describes the expansion of motorways, expressways, and the extent of motorway accessibility to population and jobs during the period of analysis. Section 5 presents some final considerations.

2. DATA AND METHODOLOGY

The diagram in Figure 1 describes the overall methodology and specific procedures undertaken using a Geographic Information Systems (GIS) environment based on version 10.8 of the ArcGIS platform marketed by ESRI (ESRI, 2022). As depicted in the figure, the creation of the georeferenced longitudinal database considered as inputs data for the road networks covering the period from 1971 to 2020 at ten-year intervals, as well as other spatial and tabular information referring to demographic and socio-economic data from the decennial population censuses. Therefore, in Figure 1, we have represented two main frames showing the specific input data and processing tasks. In the top frame, we show the data and operations relating to the construction of the road network database, whereas in the bottom frame we show the operations referring to the spatial and tabular socioeconomic data obtained from the population censuses.

The left box of the top frame shows the road network data collected. Given the different formats of the baseline road maps (digital vector formats and paper maps), several spatial processing tasks had to be performed on the data obtained from public entities and private institutions, notably: Portugal Infrastructures (IP), a state-owned company responsible for the management of the country's road network (except municipal roads) and rail network; the Army Geospatial Information Center (CIGeoE), which is an official provider of geographic/geospatial information; the Portuguese Automobile Club (ACP), the oldest motoring club in Portugal with more than 100 years and owner of a large collection of historic road maps; and *TomTom-TeleAtlas*, a Dutch multinational company specialized on the development of global location technology and one of the most important retailers

[1] Available at: https://data.mendeley.com/datasets/ry5dkty7t7.

of car satellite navigation worldwide. The tabular data associated with the road databases includes the following main attributes: type of road link, length of road link, road identifier, year of opening, and the legal speed limit. The right box of the top frame highlights the main validation procedures carried out on the tabular information, including updates, edits, topological operations, and the generation of a routing grid covering all the Portugal mainland. The grid is composed of square cells with a 500-meter length and an attributed speed of 10 km/h, and was built to support and improve route assignments, as to ensure a proper connection between municipality centroids and the road network. This routing grid was essential for the more accurate calculation of the travel time/distances between all pairs of centroids. The GIS-based models of the different road and motorway networks were then assembled in geodatabases and evaluated for their integrity, essentially through operations of vectorization, calibration, and topological analysis, which we discuss in Section 3.

The left and right boxes of the bottom frame show the spatial and tabular data obtained from the Directorate-General of the Territory (DGT), a government entity that is responsible for the establishment of standards and references in several domains (e.g., geographic information, geodesy, mapping, and land registry), and Statistics Portugal (INE), the official entity for statistics in Portugal. These data include geospatial information containing the administrative boundaries for municipalities, as recorded in the DGT's Official Administrative Map of Portugal (CAOP), their respective centroids, census population data obtained at the geographic level of the minimum subdivision of the census spatial database – the Geographic Base of Information Referencing (BGRI) –, as well as employment data collected also from the decennial censuses. We used population-weighted centroids based on the spatial distribution of the population within each municipality (instead of geographic centroids) to compute road distances and travel times between municipalities. Although mainland Portugal has 278 municipalities, to ensure data consistency across the time horizon studied, we use the pre-1998 administrative division, i.e., 275 municipalities. The integration of the GIS-based road network with this information allowed us to develop several indicators of road accessibility for population and jobs at the municipality level (see Section 4).

Figure 1. Methodology underlying the construction of the TiTuSS Transport Database

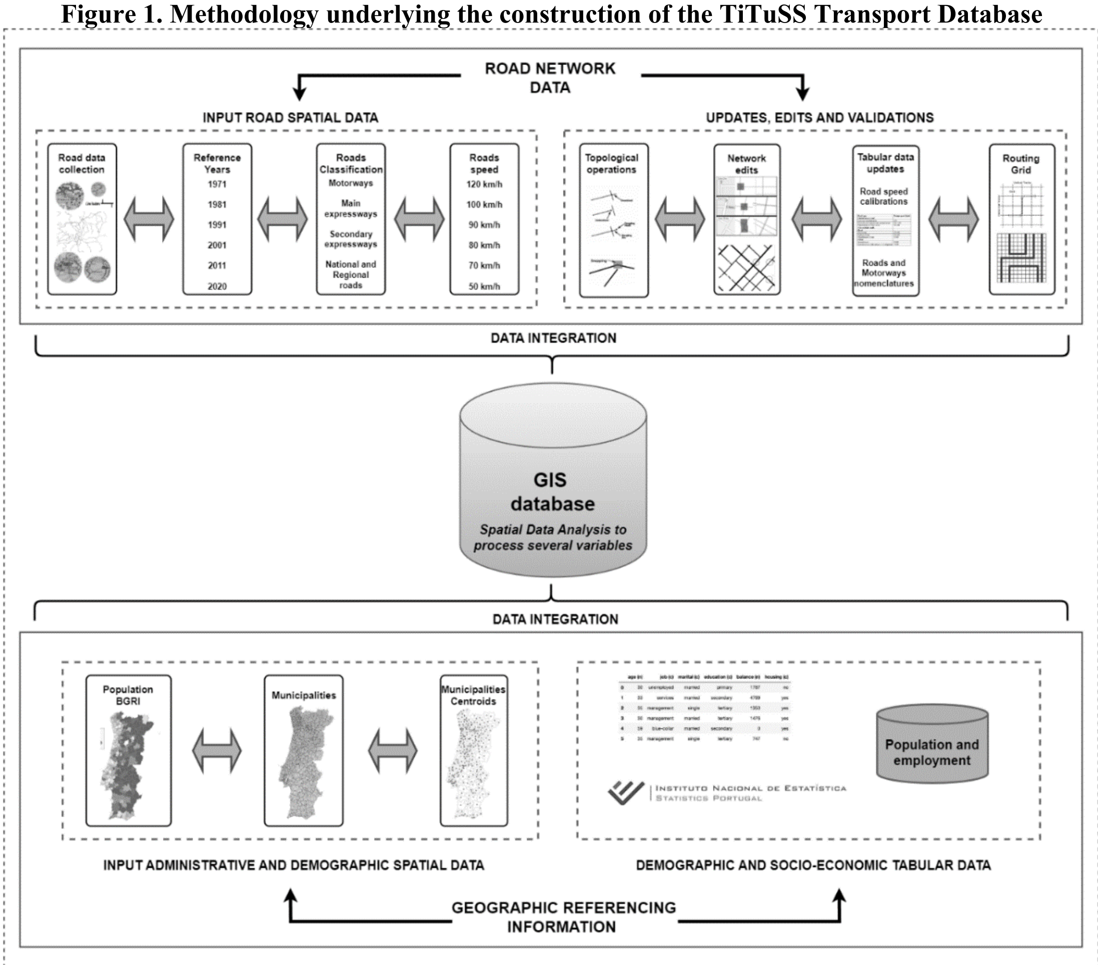


Table 1 presents the data sources and formats for each reference period. As noted above, road maps came from different entities and were in various formats, more specifically, vector format (e.g., CAD and *shapefile* format) and paper format in the case of the maps published by the Portuguese Automobile Club (ACP) for the 1970s and 1980s, which required further scanning, vectorization, and editing. The digital vector format road maps were sourced from public entities, namely the Army Geospatial Information Center (CIGeoE) and Portugal Infrastructures (IP), as well as from a private sector company, *TomTom-TeleAtlas*. In addition to these sources, we also used data from the open-source geographic database *OpenStreetMap* (OSM)[2], maintained and updated by a collaborative project, where data are collected from surveys, aerial imagery, and other free licensed geodata.

Table 1. Summary of the sources and formats of the road mapping information

Years	Road map information	Format	Source
1998	Primary	Digital (*.shp** and *.dwg** formats)	CIGeoE
1991, 2001, 2011	Primary	Digital (*.shp* format)	TomTom-TeleAtlas
1971, 1981	Auxiliary	Paper / Digital (*.pdf*)	ACP
2020	Auxiliary	Digital (*.shp* format)	IP
Various from 2004	Auxiliary	Digital (*.shp* format)	OSM

*Note: *native digital vector proprietary formats. The shapefile format (.shp), developed by ESRI, is interoperable with most GIS software packages and stores geographic and associated tabular attributes information, whereas the drawing (.dwg) format, developed by Autodesk, is native for several CAD applications, including AutoCAD.*

Given the multiple sources of road network information, we made the following decisions. The construction of the 1981 road network was primarily based on downgrading operations of the digital vector map from CIGeoE referring to the year 1998. The 1971 road network was then built from the 1981 network, after the validation of the necessary downgrades. The road networks for 1991, 2001, and 2011 were primarily based on maps from *TomTom-TeleAtlas*, which were already available for each of those years. The construction of the 2020 road network was based on the 2011 network after the validation of the necessary upgrades. The road networks obtained from ACP, IP, and OSM were used as auxiliary sources in the construction of the road networks in each period with the specific purpose of complementing information from the primary sources previously described. They provided useful information for the processes of verification, validation, and integration of the different networks, notably the operations of upgrading and downgrading for the 2020 and 1971 networks respectively.

In addition to the road mapping information in Table 1, we also considered information about the different road networks compiled in a technical study produced by Portuguese scholars, Sousa et al. (2011), who analyzed the evolution of the road network from 1983 to 2009. More specifically, the maps illustrating the most relevant updates of the road network were used to visually verify their agreement with the road networks we edited, especially the road networks referring to 1991 and 2001.

3. CONSTRUCTION AND VALIDATION OF THE ROAD NETWORKS

This section describes the various procedures undertaken to produce a single harmonized and internally coherent sequence of road networks covering the period from 1971 to 2020. Following the overall approach depicted in Figure 1, we carried out several measures to ensure the resulting georeferenced longitudinal road networks are valid for analyses of road--based accessibility.

[2] Data for Portugal obtained from: https://download.geofabrik.de/europe/portugal.html.

3.1. Road typologies and free-flow speeds

The classification of roads changed over the timeline of the study according to the prevailing National Road Plan (PRN). The first PRN dates from 1945, as published in the Decree-Law 34593 (1945), and was revised by the PRN 1985, that is, the Decree-Law 380 (1985), and the PRN 2000, that is, the Decree-Law 222 (1998), which is still in effect today. According to the current national road plan, the National Road Network is composed by the Fundamental National Network, which contains the principal routes (IPs), and the Complementary National Network, which contains the secondary routes (ICs) and national roads. The majority of IPs and many ICs make up the motorway network, in which case their designation starts by the letter A referring to "Autoestrada" (i.e., motorway in Portuguese). IPs, ICs, national, and regional roads are managed at the level of central government by Portugal Infrastructures, while municipal roads are managed at the local level by municipalities. The types of roads considered in our study are summarized in Table 2 and can be described as follows:

- *Motorways:* these roads have physically separated carriageways (dual carriageway), each with at least two traffic lanes, and grade separated junctions. Motorways comprise a great part of principal routes (IPs) and several secondary routes (ICs). These roads are restricted to motorized vehicles with a minimum of 50 cylinder capacity (cc).
- *Expressways (Main and Secondary)*: these roads also have dual carriageway, each with at least two traffic lanes. Yet, these characteristics are recommended and not mandatory, i.e., some of these roads may have single carriageway with three or two lanes, or even dual carriageway with three lanes or two lanes (one by each direction). Road junctions tend to be grade separated; however, in some specific situations at-grade road crossings could be allowed. For the purposes of our database, we consider that main expressways are those that are part of the principal routes (IPs), while secondary expressways are part of the secondary routes (ICs). We exclude from this class a few expressways which already have a reserved motorway label and include them in the *Motorway* type group. Expressways are also restricted to motorized vehicles with a minimum of 50 cc.
- *National Roads:* these roads constitute the second component of the Complementary National Network, covering all the country beyond the *Expressways* and *Motorways.* Normally, these types of roads have a single carriageway with two traffic lanes (one by each direction) and level crossings (road intersections). However, in specific situations they could have more than two traffic lanes, dual carriageway and grade separated junctions. An example could be ring or outer circular roads in urban or suburban areas, as well as other corridors with heavy traffic volumes. The free-flow speed considered on these roads can vary depending on the road's terrain and pavement conditions.
- *Regional Roads:* these roads have supra-municipal interest and are complementary to the *National Roads*. They generally have lower speed limits than national roads. Furthermore, similarly to national roads, some of their segments may also include dual carriageway, and grade separated junctions. Likewise, the free-flow speed considered can also vary depending on the road's terrain and pavement conditions.
- *Municipal/Local roads:* these roads are the sole responsibility of municipalities. They include the roads connecting different civil parishes and these with the seat of the municipality, as well as other roads inside urban areas. The speed limit can vary depending on the urban context and road conditions; for example, speeds inside urban areas are generally limited to 50 km/h. In addition, they may also include dual carriageway (with two or more traffic lanes), and grade separated junctions. Given the massive number and capillarity of municipal roads, and the fact that many were built to serve rural, forested areas and small hamlets, our analysis considers the municipal roads that correspond to urban connections (e.g., city streets and avenues) in metropolitan areas and in other urban areas. Overall, this corresponds to about 1/3 of the total length of municipal roads in Portugal.

The speed limits associated with each type of road were assigned to each respective road segment in the GIS database according to what is established in each PRN. These speeds were treated as free-flow (i.e., assuming no road congestion) and were used in the computations of travel times (after the validation process described in Section 3.2) along the road network between each pair of municipalities. Table 2 shows the road classification and the reference free-flow speeds used.

Table 2. Classification of roads and free-flow speeds by type of road

Classification	Picture	Dual Carriageway	Reference free-flow speed (km/h)
Motorways		Yes	120
Main / Secondary Expressways	 	Yes	100
		No	90 to 100
National Roads		No	70 to 90
Regional Roads		No	70 to 80
Municipal / Local Roads	 	No	50 to 70
		Yes	70 to 80

Note: Pictures sourced from Portugal Infrastructures (IP) and Wikimedia Commons (WC).

3.2. Validation tests and quality control procedures

3.2.1 Adjustments and updates of free-flow speeds

The main purpose of this process consisted in the verification, update, and validation of the free-flow speed limits (see Table 2) in the different periods of analysis. Given the long timespan of the period studied, many roads were improved (e.g. road category upgrades or rehabilitation works) and thus had to have their speed limits updated over the years. In addition, several speed limit rectifications had to be performed. Since the road mapping information for different periods comes from different sources, there were differences in the level of detail for each road section. Those small differences were rectified through harmonizing the free-flow speeds in the problematic road segments. In addition, in some cases the maximum legal speed limits attributed to each road type had to be adjusted to take account of speed limitations due to adverse topographical conditions. Therefore, in some areas (mainly in the North region), road speeds were reduced from the original speed by 40% due to the terrain topography. To be more precise, we superimposed a terrain basemap on the road network to identify the municipalities with an Average Terrain Elevation (ATE) greater than 500 meters, and then selected the road sections that needed to have their road speed limits reduced.

3.2.2 Topological network analysis

The topological analysis carried out evaluated the logical consistency of the spatial data, notably the existence of integrity and connectivity in the spatial relationships and between the road networks referring to the different time periods. According to ESRI (2021), the verification of logical consistency requires that the data are topologically correct and follows a set of rules to enable the GIS database to more accurately model geometric relationships. This analysis was carried out for each period of the study using ESRI's *ArcGIS* spatial tool *Topology* which is based on a set of rules of integrity and topological behavior (for more details see Appendix B).

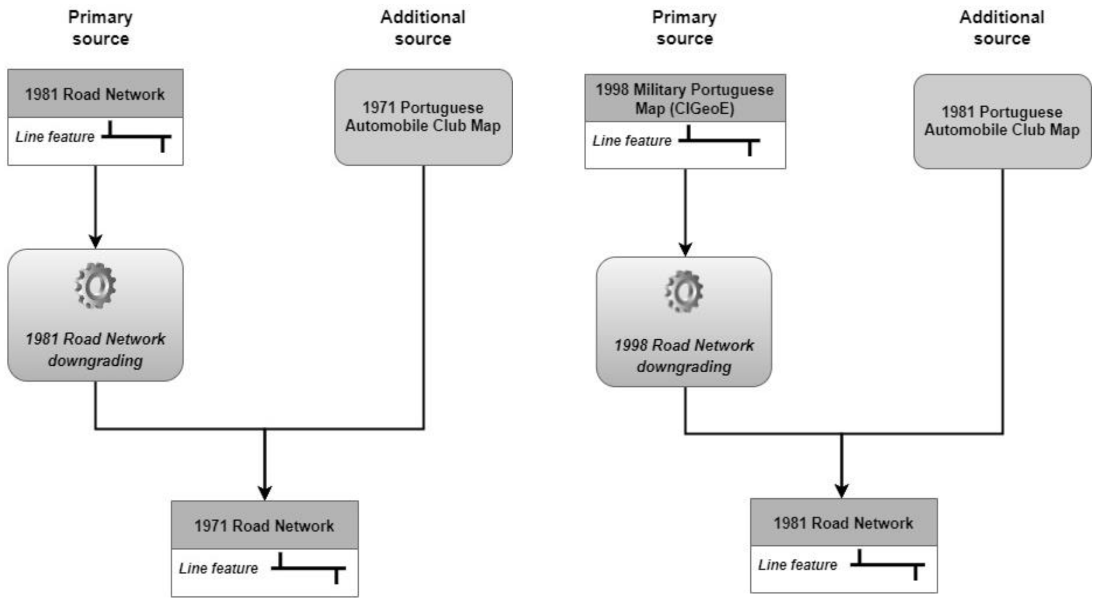
3.3. Road networks construction methodology

3.3.1 The road networks of 1971 and 1981

Figure 2 shows the workflow of the construction of the 1971 and 1981 road networks. The construction of the road network for 1971 was implemented by applying downgrading operations to the road network of 1981. This basically consisted of deleting or shortening the road sections present in the 1981 digital vector road network, but which were inexistent in 1971. Downgrading operations were supported by the information contained in the attributes table of the 1981 digital vector road network, which indicated the year of opening of each road section. In addition, we used supplementary information from existing road maps from the Portuguese Automobile Club (ACP) for 1971. Moreover, verification tests of the shortest path and total travel times between each pair of municipalities were made using the network and the routing grid created for this purpose.

The construction of the 1981 road network was fundamentally based on the reference GIS-based road map obtained from the Army Geospatial Information Center (CIGeoE) referring to the year 1998 (see Table 1). A series of downgrading edits were carried out based on information about the opening year of road sections in the attribute table associated with the CIGeoE map. The resulting road map for 1981 was then compared to the ACP paper format road map for 1981.

Figure 2. Workflow of the construction of the road networks in 1971 (left) and 1981 (right)



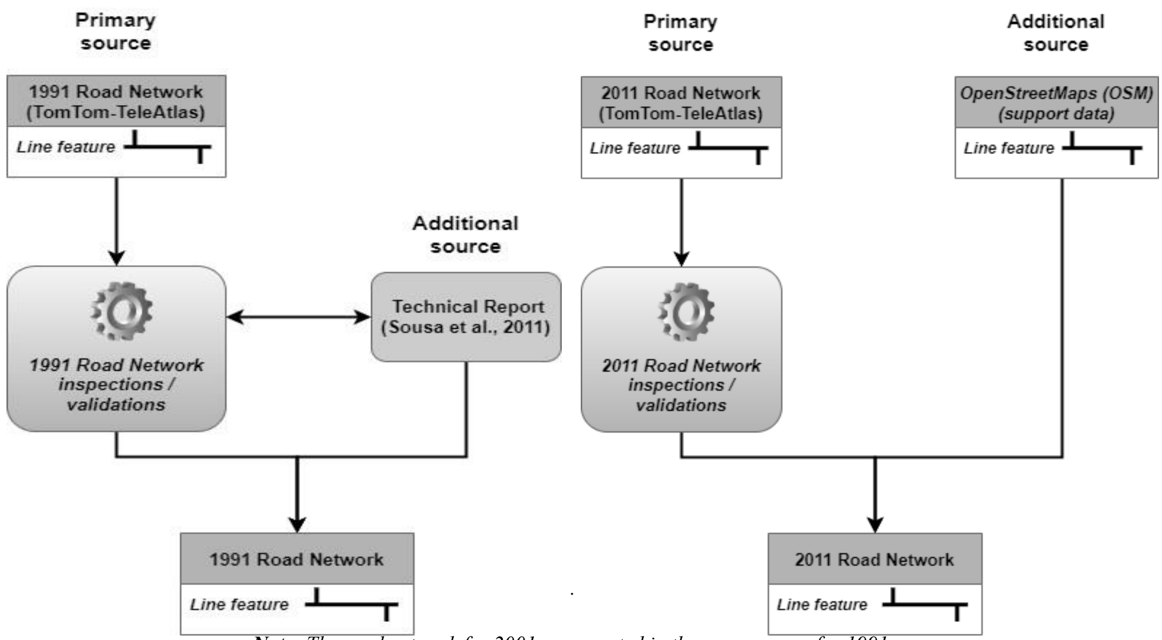
3.3.2 The road networks of 1991, 2001, and 2011

The road networks for the years 1991, 2001, and 2011 were derived from reference maps obtained from *TomTom-TeleAtlas* (see Table 1). To ensure comparability between the road networks for these years and the 1971 and 1981 road networks, we first applied a coordinate system transformation between primary sources to overcome the difference between the military coordinate system and the coordinate systems used in georeferenced maps produced by non-military entities. The maps were then overlapped with each other, assessed for comparability, and revised for coherence.

Figure 3 shows the workflow of the construction of the 1991 and 2011 road networks. Since the road network data for 2001 was evaluated and validated in the same way as for 1991, we present the workflow only for the years 1991 and 2011. The construction of the road network for 1991 was based exclusively on the *TomTom-TeleAtlas* road maps for that year. The network data was evaluated according to its integrity and validated using a set of quality control operations to identify network inconsistencies, including the occasional implementation of small vectorizations in the vector map and updates to the tabular information in the respective attribute table. Verification tests for the shortest path and total travel times between each pair of municipalities using the routing grid created were also implemented. In addition, we also used the documentation provided by Sousa et al. (2011) to compare our networks to those produced by the authors.

The construction of the road network for the year 2011 followed the same approach as for the year 1991 and 2001, and, in addition, included checking for necessary updates (or possible downgrades) based on information from the open-source geographic database OSM.

Figure 3. Workflow of the construction of the road networks in 1991 (left) and 2011 (right)

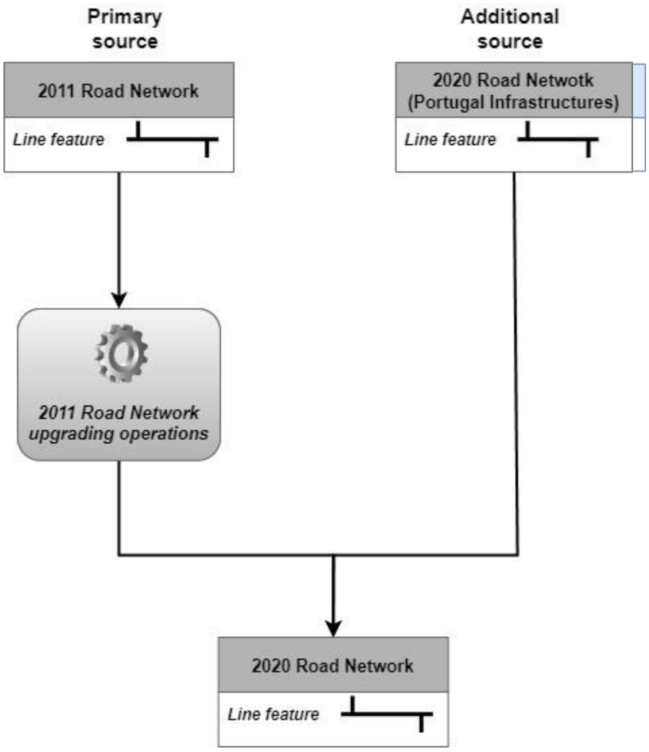


Note: *The road network for 2001 was created in the same way as for 1991.*

3.3.3 The road network of 2020

Figure 4 shows the workflow of the construction of the 2020 road network. The primary source was the 2011 road network obtained following the workflow described in Figure 3, which served as the basis for the upgrading operations referring to the motorways and expressways identified from the auxiliary vector road map for 2020 (see Table 1) obtained from Portugal Infrastructures (IP).

Figure 4. Workflow of the construction of the road network in 2020



4. EVOLUTION OF MOTORWAYS, EXPRESSWAYS, AND ROAD ACCESSIBILITY TO PEOPLE AND JOBS

This section presents a brief description of the changes occurred in motorways and expressways between 1971 and 2020 and the consequent improvements in road-based accessibility to people and jobs.

Figure 5 shows the expansion of motorways and expressways in Portugal over the period. In 1971 and 1981, both motorways and expressways were practically inexistent (in 1971, motorways and expressways added up 75 km and 5 km, respectively), and largely limited to the metropolitan areas of Lisbon and Porto. Regarding the Sines region (a town in the south west of the country), the main reason for the early development of accessibilities was the expansion of the Sines deep-water port area, and the growth of other related industrial projects, namely the installation of the petrochemical industrial park and the coal thermoelectric central. In 1981, there were around 162 km of motorways and 29 km of expressways, representing an annual average growth rate (AAGR) of 8.0% and 19.2%, respectively, from 1971.

Between 1981 and 1991, the network experienced considerable expansion. The main corridor of the motorway network, the A1 motorway linking Lisbon to Porto, was completed in 1991. Regarding main expressways (IPs), the fully operational IP5 (Aveiro/Vilar Formoso) – an important international west-east corridor –, the north section of IP4 (Amarante/Vila Real) and the interior central region IP2 section (Castelo Branco/Fratel) were the most notable advances. The length of motorways and expressways reached 550 km and 444 km in 1991, representing an AAGR from 1981 of 13.0% and 31.4%, respectively.

The length of motorways and expressways continued to increase at a substantial pace between 1991 and 2001, reaching 1 664 km (i.e., an AAGR of 11.7%) and 920 km (7.6%) respectively. This period saw the completion of some important connections to Spain, namely, the west-east motorway corridors A6 (Lisboa/Elvas) and A22 (Albufeira/Vila Real de Santo António), this last one in the southeast region, as well as the A3 motorway between Porto and Valença. There were other relevant advances, notably the completion of some important main expressways, such as the IP3 (Coimbra/Viseu) and IP4 (up to Bragança), as well as the improvement in connections to low-density regions in the interior of the country, e.g., the sections of IP2 (Portalegre/Estremoz). Regarding secondary expressways (ICs), the IC8 (Pombal/Proença-a-Nova) was a relevant advance.

The length of motorways and expressways reached 2 877 km and 1 107 km in 2011, corresponding to an AAGR of 5.6% and 1.9% from 2001, respectively. This corresponds to the period in which the motorway network approached a consolidated state, after the completion of important north--south motorway corridors connections, like the A2 (Lisboa/Albufeira) and A24 (Chaves/Viseu), as well as of the A22 south west-east corridor (Lagos/Vila Real de Santo António). Moreover, new motorway sections were constructed in the (already well-served) metropolitan areas of Lisbon and Porto and along the coast between these two regions. Additionally, some main expressways were also upgraded to motorway status during this period, namely the A25 (Aveiro/Vilar Formoso) – formerly IP5 – and the A23 (Torres Novas/Guarda), upgraded from the former IP2. At the expressways level, the conclusion of the north section of IP2 (Macedo de Cavaleiros/Trancoso) was the most relevant improvement. Finally, the evolution from 2011 to 2020 was rather small; in fact, the motorway network almost stopped growing after 2013 when the motorway network was essentially completed. The main improvements in the motorway network during this period were the completion of the A4 (Porto/Bragança) in the northeast region (mostly from the upgrade of IP4) and the A13 (Tomar/Coimbra) in the centre region. Concerning expressways, connections (of already existing IPs and ICs) in the west-east (centre and northeast regions) and south interior corridors were also concluded. The length of motorways and expressways in 2020 was 3 164 km and 1 141 km, corresponding to an AAGR from 2011 of 1.1% and 0.3%, respectively.

The total motorway length (3 164 km) corresponds to approximately 100 km more than the official value reported by Eurostat. The difference can be mainly explained by the definition of motorways used in this study, which assumes that all expressways (IPs and ICs) that meet certain specifications (i.e., speeds of 120 km/h and other specifications described in Section 3.1.) and have a reserved motorway label should effectively be treated as motorways.

Table 3 presents a summary of basic descriptive statistics for the measures of road and motorway accessibility, namely: length of motorways and expressways, number of motorway access ramps, distance to the nearest motorway access ramp, the shares of municipalities, population, and jobs with access to a motorway ramp within a certain travel time, and an indicator of market potential for both population and jobs. The indicator of market potential is described in equation (1). The measures of road-based distance and travel time used in the computation of our indicators were calculated using 1981 population-weighted centroids for all municipalities. Data for population and jobs were obtained from the population census.

$$MP_i = \sum_{j \neq i} \frac{O_j}{c_{ij}} \qquad (1)$$

MP_i denotes the potential population (or jobs) accessible to municipality i, and consists of the summation of the population ($O_j = POP_j$) or jobs ($O_j = JOB_j$) in each municipality j, discounted for the travel time ($c_{ij} = tt_{ij}$) or road distance ($c_{ij} = dis_{ij}$) between each pair of municipalities i and j. The travel times tt_{ij} and road distances dis_{ij} were computed using the municipality's 1981 population-weighted centroids, as referred previously. The indicator of market potential captures the combined effects of economic mass (measured either by population or jobs) and road improvements (measured in the origin-destination road distances and travel times). For a full list of the variables included in the database, see Appendix A.

Table 3 shows that the size of the motorway network improved massively during the last two decades of the 20th century, as depicted in the maps of Figure 5. These improvements are reflected in the substantial reduction of the average distance to the nearest motorway access ramp, which in 1971 was 118 km, falling to 96 km in 1981, 65 km in 1991, 26 km in 2001, 20 km in 2011, and 16 km in 2020. Expressways also increased substantially, but there is considerable variation across typologies. Secondary expressways (ICs) limited to 100 km/h grew significantly only after 2011 due to improvements in technical standards carried out on this type of roads. This explains the reduction in the total length of secondary expressways limited to 90 km/h between 2011 and 2020, as some of these were upgraded to 100 km/h. As for the main expressways (IPs), the observed reduction in their length in the later periods of 2011 (for IPs limited to 90 km/h) and 2020 (for IPs limited to 100 km/h) can be explained by the upgrading of some IPs to motorway status.

Figure 5. Evolution of motorways and expressways in Portugal between 1971 and 2020

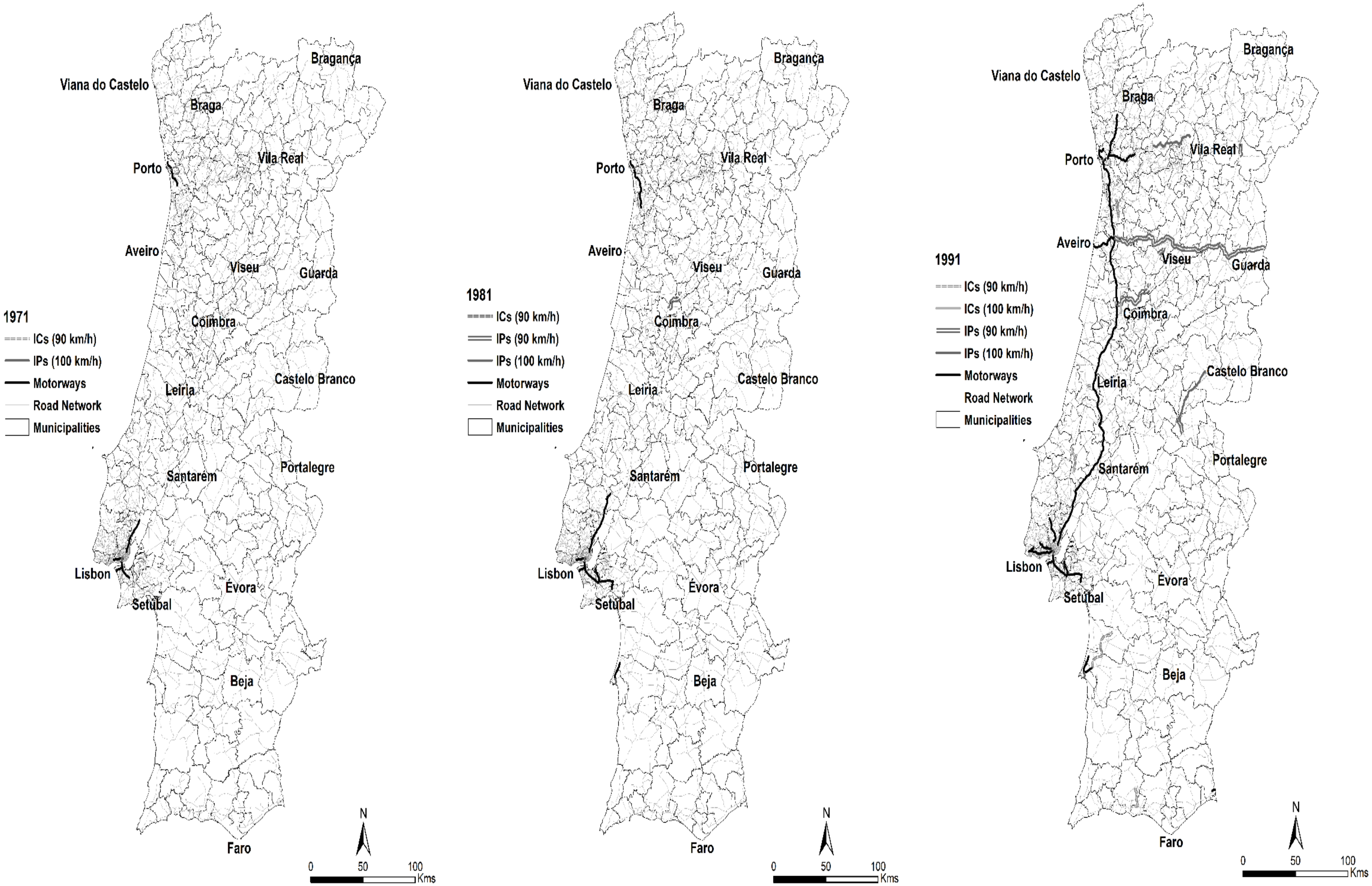
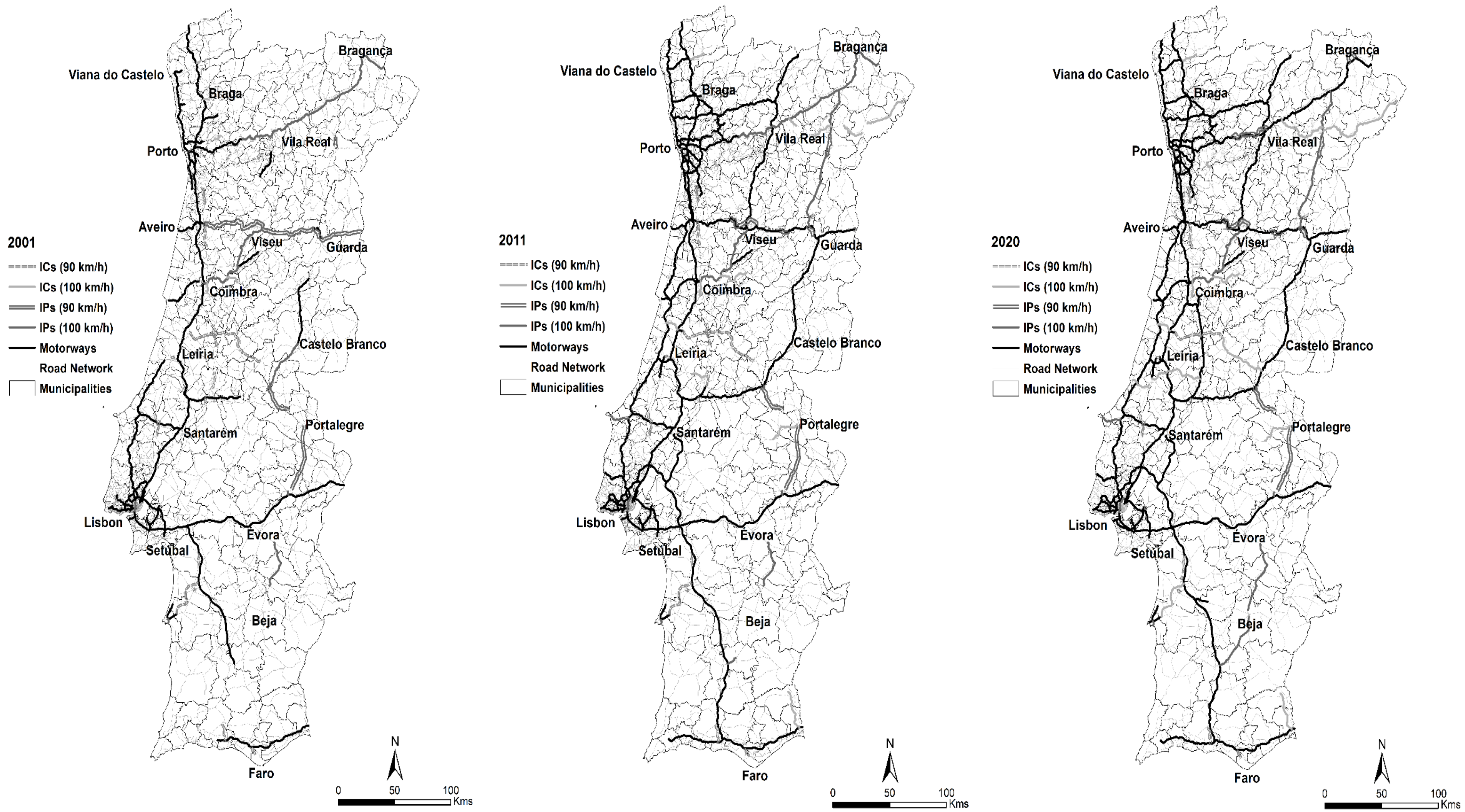


Figure 5. Evolution of motorways and expressways in Portugal between 1971 and 2020 (cont.)



As expected, we also observe strong improvements in the territorial coverage of motorways and the extent of the total population and jobs served by motorways. Up to 1981, less than 10% of the municipalities were within 15 minutes of the nearest motorway access ramp, rising to almost 20% in 1991, 44% in 2001, 56% in 2011, and 61% in 2020. If we consider 30 minutes as the reference, in 1981 only 16% of the municipalities had access to a motorway in that time band, rising to 32% in 1991, 69% in 2001, 79% in 2011, and 82% in 2020. In 1981, less than 30% of the municipalities were within 60 minutes to the nearest motorway, in contrast to more than 50% in 1991, and more than 90% in 2001, reaching 96% and 98% in 2011 and 2020, respectively. In other words, at the beginning of the 21st century already nearly all municipalities were within 60 minutes of a motorway access ramp and over 2/3 were within 30 minutes.

The increase in the coverage of the population served by motorways is also notable. Up to 1981, less than 1/3 of the population was within 15 minutes to the nearest motorway ramp; the share exceeded 50% by 1991, reaching 75% in 2011, 84% in 2011, and 86% in 2020. If we consider instead the population within 30 minutes to the nearest motorway, we observe that nearly all the population had access to motorways after 2001 – i.e., 91%, 95%, and 96% in 2001, 2011, and 2020 respectively –, which is in great contrast to only 35% of the population in 1971, rising to 44% and 63% in 1981 and 1991, respectively. Motorway access levels are much larger for the 45- and 60-minutes time intervals.

Regarding the coverage of jobs, the analysis could only be done for the years from 1991 to 2020, due to lack of data for the previous years. In 1991 we already have one of the most important axis of the motorway network concluded – i.e., the A1-A3 corridor connecting Lisbon to Porto (and almost to Braga), as shown in Figure 5. This corresponds to the regions with the greater concentration of jobs, which helps explain why in 1991 we have already 71% of jobs within 15 minutes from the nearest motorway ramp. This percentage increased to 91% in 2001, 95% in 2011, and 96% in 2020. Considering the share of jobs within 30 minutes to the nearest motorway, we observe that in 1991 almost 80% of jobs had access to motorways, with nearly full coverage being achieved in the following years: 96% in 2001, 98% in 2011, and 99% in 2020. The share of jobs within 45 minutes or 60 minutes from the nearest motorway was already very high in 1991, i.e. 83% and 86% respectively, reaching practically 100% from 2001 onwards.

Concerning market potential, this gravity measure was computed according to equation (1) to evaluate accessibility to population and jobs (only from 1991 onwards) in each year of analysis. The values reported in Table 3 represent the simple mean and median values of market potential across municipalities, calculated using both the travel time and road distance between municipalities. Given the reported improvements in the road network, we expect both road distances and travel times to have reduced over the period across municipalities, but the direction of change in population (and jobs) is less obvious and will vary across municipalities. Consequently, the overall effect reflected in the value of market potential is not self-evident. We observe that the mean and median values of the market potential indicator tend to increase over the period, except for 2020. Given the limited change in road accessibility between 2011 and 2020, the slight decrease in the mean and median values of the market potential may reflect the reduction in population size by 1.9% between 2011 and 2021, according the 2021 population census. Given the very heterogeneous performance across mainland municipalities, it is important to assess the change in the value of the market potential indicator for different regions of the country, contrasting urban with rural areas, coastal with interior areas, etc. This, however, is not within the scope of this paper, but is an interesting avenue for future research.

Table 3: Summary statistics of the variables included in the longitudinal spatial database

	1971	1981	1991	2001	2011	2020
Length of motorways (km)	77	164	552	1 673	2 886	3 173
Number of motorway access ramps	63	86	187	515	761	822
Average distance to nearest motorway access ramp (km)*	118	96	65	26	20	16
Length of main expressways, 100 km/h (km)	3	6	97	365	435	322
Length of secondary expressways, 100 km/h (km)	0	0	8	38	247	431
Length of main expressways, 90 km/h (km)	0	18	247	263	157	215
Length of secondary expressways, 90 km/h (km)	2	5	92	254	268	173
Share of municipalities within* …						
15 min to nearest motorway access ramp (%)	5	9	18	44	56	61
30 min to nearest motorway access ramp (%)	11	16	32	69	79	82
45 min to nearest motorway access ramp (%)	17	21	43	85	92	95
60 min to nearest motorway access ramp (%)	22	28	55	92	96	98
Share of population within* …						
15 min to nearest motorway access ramp (%)	26	33	52	75	84	86
30 min to nearest motorway access ramp (%)	35	44	63	91	95	96
45 min to nearest motorway access ramp (%)	43	50	73	96	98	99
60 min to nearest motorway access ramp (%)	47	58	81	97	99	100
Share of jobs within* …						
15 min to nearest motorway access ramp (%)	-	-	71	91	95	96
30 min to nearest motorway access ramp (%)	-	-	78	96	98	99
45 min to nearest motorway access ramp (%)	-	-	83	98	99	100
60 min to nearest motorway access ramp (%)	-	-	86	99	100	100
Market Potential values, for population accessibility*….						
Mean, considering travel time	54851	66195	79080	97201	106461	105338
Median, considering travel time	53127	61851	73552	91555	100643	99219
Mean, considering road distance	59033	67960	66613	69719	71140	69721
Median, considering road distance	59769	67034	64145	66327	66613	64899
Market Potential values, for jobs accessibility*….						
Mean, considering travel time	-	-	33298	44289	44061	42681
Median, considering travel time	-	-	30059	40627	41013	39675
Mean, considering road distance	-	-	27665	31401	29203	28042
Median, considering road distance	-	-	25564	28447	26307	25132

*Note: *calculations based on the municipality population-weighted centroids of 1981.*

5. FINAL CONSIDERATIONS

This work described the methodology and quality control procedures implemented to build a new longitudinal spatial database which integrates information for the road networks with demographic, administrative, and socioeconomic information for the municipalities of mainland Portugal over the period from 1971 to 2020. The resulting database can be used to study the effects of improved road accessibility on multiple socioeconomic outcomes in Portugal (e.g., population growth/decline, employment growth/decline, regional cohesion, urbanization patterns, etc.) over a considerable long period of 50 years.

Portugal's road network experienced a strong investment in motorways and expressways after the 1980s, especially after the country joined the now EU and gained access to European regional development funding to improve its public capital infrastructure, as mentioned in Pereira and Pereira (2016). There are previous works to ours that also constructed spatial databases of road networks for Portugal, namely, Sousa et al. (2011) and Cruz et al. (2021). Our work adds to these existing databases in several ways. We consider a longer period by including data for 1971 and the more recent years 2011 and 2020. Similarly to Cruz et al. (2021), our database from Afonso et al. (2023) is publicly available for free, in contrast to the database produced by Sousa et al. (2011) which is not publicly available. There are also differences in terms of the transport indicators developed and the geographical units to which they refer. The database produced by Cruz et al. (2021) considers a wider range of transport indicators, referring, among others, to road and rail access to the main airports and ports in mainland Portugal in the period from 1981 to 2019, but the indicators are provided only at the level of NUTS III regions, which correspond to aggregations of municipalities.

Although the database and analysis presented in this study refer to the road network, we have also developed simple measures of the railway network, namely the number of active railway stations in each municipality and the road-based distance and travel time to the nearest active railway station, which are also included in our database. We hope to release new versions of the database in the future that include more detailed measures of rail accessibility. In contrast to the large expansion of motorways and expressways in this period, railways experienced strong disinvestment, both in terms of line closures and lack of upgrading of the infrastructure. Portugal has one of the least dense and least competitive passenger railway networks in the EU and is the only non-island country with a motorway network larger than the railway network. Between 1971 and 2020, more than 1 000 km of railways were closed, corresponding to about 29% of the network.

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APPENDIX A

Table A.1. Variables in the database developed by Afonso et al. (2023), described in this study

Variable		**Variable definition**	**Units**	**Years**
Identifier variables	OID	Object identifier for municipalities	N/A	Time-invariant
	YEAR	Year of analysis	N/A	1971-2020
	NUTS2	NUTS II region (Nomenclature of Territorial Units)	N/A	Time-invariant
	NUTS3	NUTS III region (Nomenclature of Territorial Units)	N/A	Time-invariant
	DT81	Official administrative code of district according to the territorial division of 1981	N/A	Time-invariant
	DTCC81	Official administrative code of municipality according to the territorial division of 1981	N/A	Time-invariant
	DISTRICT	Name of district	N/A	Time-invariant
	MUNICIPALITY	Name of municipality	N/A	Time-invariant
	AREA	Territorial area of municipality	Km2	Time-invariant
Motorways & Expressways	EXT_MTW	Length of the motorway network	Meters (m)	1971-2020
	DEN_MTW	Density of the motorway network (EXT_MTW/AREA)	m/Km2	1971-2020
	EXT_MEXP	Length of the main expressways (IP)	Meters (m)	1971-2020
	DEN_MEXP	Density of the main expressways (IP) (EXT_MEXP/AREA)	m/Km2	1971-2020
	EXT_SEXP	Length of the secondary expressways (IC)	Meters (m)	1971-2020
	DEN_SEXP	Density of the secondary expressways (IC) (EXT_SEXP/AREA)	m/Km2	1971-2020
	MTW_AR	Number of motorway access ramps	Number (n)	1971-2020
	DEN_MTW_AR	Density of motorway access ramps (MTW_AR/AREA)	n/Km2	1971-2020
	TT_MTW_AR	Time travel to the nearest motorway access ramp (using 1981 population-weighted municipality centroids)	Minutes (min)	1971-2020
	RDIST_MTW_AR	Road distance to the nearest motorway access ramp (using 1981 population-weighted municipality centroids)	Meters (m)	1971-2020

Railways	NUM_ACTST	Number of active train stations	Number (n)	1971-2020
	TT_ACTST	Time travel to the nearest active train station (using 1981 population-weighted municipality centroids)	Minutes (min)	1971-2020
	RDIST_ACTST	Road distance to the nearest active train station (using 1981 population-weighted municipality centroids)	Meters (m)	1971-2020
Geographic variables	SDIST_PTCT	Straight line distance to Portuguese coast (using 1981 population-weighted municipality centroids)	Meters (m)	Time-invariant
	SDIST_PTBD	Straight line distance to Portuguese border (using 1981 population-weighted municipality centroids)	Meters (m)	Time-invariant
	CC81_ALT	Altitude of the 1981 population-weighted centroids	Meters (m)	Time-invariant
	ATE	Average terrain elevation	Meters (m)	Time-invariant
	STDTE	Standard deviation of terrain elevation (terrain ruggedness)	Meters (m)	Time-invariant
Market Potential	MP_PPA_TT	Market Potential - Potential Population Accessibility (travel time)	N/A	1971-2020
	MP_PPA_RDIST	Market Potential - Potential Population Accessibility (road-based distances)	N/A	1971-2020
	MP_NUTS3_PPA_TT	Market Potential - Potential Population Accessibility for the same NUTS3 municipalities (travel time)	N/A	1971-2020
	MP_NUTS3_PPA_RDIST	Market Potential - Potential Population Accessibility for the same NUTS3 municipalities (road-based distances)	N/A	1971-2020
	MP_PJA_TT	Market Potential - Potential Jobs Accessibility (travel time)	N/A	1991-2020
	MP_PJA_RDIST	Market Potential - Potential Jobs Accessibility (road-based distances)	N/A	1991-2020
	MP_NUTS3_PJA_TT	Market Potential - Potential Jobs Accessibility for the same NUTS3 municipalities (travel time)	N/A	1991-2020
	MP_NUTS3_PJA_RDIST	Market Potential - Potential Jobs Accessibility for the same NUTS3 municipalities (road-based distances)	N/A	1991-2020

APPENDIX B

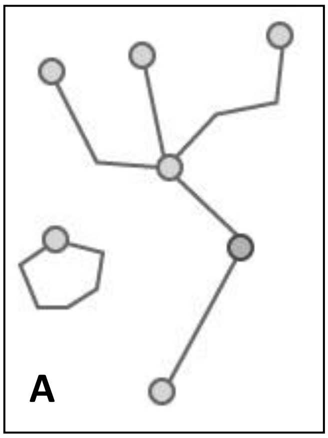
Topological network analysis

The topological network analysis was implemented using *ArcGIS* procedures and considered the following three rule: A) *Must not have pseudo nodes*; B) *Must not have dangles; C) Must Not overlap*.

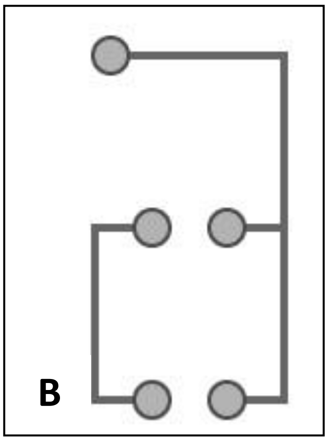
A. Must not have pseudo nodes. As mentioned in ESRI (2021), the objective is to avoid having intermediate nodes on a line. A line must connect to at least two other lines at each endpoint. This rule is useful to clean up data with inappropriately subdivided lines that can lead to so-called pseudo-nodes that should be deleted from the road network.

B. Must not have dangles. As referred in ESRI (2021), the objective is to avoid having breaks along the line's connections. A line feature must touch lines from the same feature class at both endpoints. So, when an endpoint is not connected to another line, due to an overshoot (line crosses too far over another line), or an undershoot (line is not long enough to meet the other line) we face a dangle error and it should be rectified.

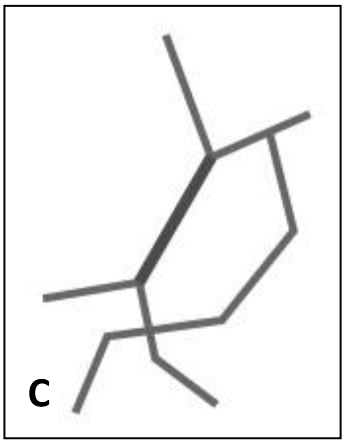
C. Must not overlap. As mentioned in ESRI (2021), this rule is used to avoid having duplicated line segments, which means that there should be no overlapping of line segments.



The darker point represents a pseudo node between the two blue endpoints of the segment.



The points show examples of dangles: endpoints with no connection to other line segments.



The darker line segment overlaps with the grey one, creating a duplication of segments.

Note: Pictures sourced from ESRI (2021).