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Accessibility and Public Transport Mobility for a Smart(er) Island: Evidence from Sardinia (Italy)

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A R T I C L E I N F O

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A B S T R A C T

The purpose of this paper is to highlight the critical aspects of islands context transportation accessibility by suggesting a more innovative, safer, and more sustainable framework for public transport service (PTS) and place-based organisation, as well as by integrating the latest tendencies in mobility. Specifically, this research focuses on multimodal integration models for PTS that consider the existing infrastructure system and the socioeconomic issues typical of an island environment. This topic has received inadequate consideration in the scientific literature on islands. To achieve these aims, an analytical-numerical approach is adopted. Starting from initial origin-destination matrices (O/D) surveyed by the National Institute of Statistics (ISTAT), a methodology was implemented to compute the geographical distribution of trips, and thereafter, the values distributed over the whole region were interpolated by Surfer software with the Kriging method. This methodology was applied to the Sardinia case study particularly emblematic because it has seen a tremendous transition over the previous decades, resulting in a massive socio-economic gap between inland and coastal areas, that led to an increase in private vehicles for transportation purposes, primarily for business and pleasure. The application, replicable in other islands that have highlighted the same socio-economic problems linked to poor mobility planning, shows an accessible spatial planning approach, combining PTS and rental for driver services, by considering the principles and issues of island contexts. This research gives an important scientific contribution by emphasising the quality of transport infrastructures, place-based organisation, population distribution, and physical configuration of the Insular Region, as well as by considering the most pressing issues of island contexts. Findings could help island governments in revising their policy and practice of transport, accordingly.

1. Introduction

The high efficiency of an island's transportation network is vital for economic, social and territorial development (Smart Islands Projects and Strategies, 2016; C 306/51, 2017; Smart Island World Congress, 2018; Desogus et al., 2019; Garau et al., 2019a). This is primarily due to the interdependence of different areas (the inland and coastal ones), which, in a geographically limited content, require the adoption of integrated planning between public and private transport by considering the socio-demographic characteristics of each area and the physical configuration of the territory (Garau et al., 2019b; Barabino et al., 2022). As a result, this study will use the concept of insularity in connection to mobility to suggest a more innovative Public Transport Service (PTS) planning system that can adapt to the intrinsic characteristics of the island context.

In recent years, the use of data and digital technologies in the mobility sector enabled many island governments to enhance and increase the efficiency of their public transportation services (Ibrahim, 2003; Lo et al., 2008; Yadav et al., 2017; All Ireland Smart Cities Forum, 2022; Smart Nation Singapore, 2022). Recognising the importance of Intelligent Transport Systems (ITS) in planning the whole island area, these governments have adopted integrated policies and regulations that include the full lifecycle of transport facets such as infrastructure systems, integrative services, and customer information (Ibrahim, 2003; Proskawetz, 2013; Tilocca et al., 2017; Coni et al., 2018; European Commission, 2022a). However, many islands have accessibility issues, limited market opportunities, and high costs associated with essential public service supply (COM 616 final, 2008). Additionally, island governments' transportation policies should include several measures tailored to local and geographical characteristics that promote

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socioeconomic development in a geographically complex, closed, and limited system (European Parliament, 2003). In these contexts, the concept of accessibility becomes a priority to alleviate the economic, social, and demographic gap that exists between coastal and inland areas (Cohesion Policy Department, 2018; Garau et al., 2020a; Pinna et al., 2021). The literature has extensively shown how, in an insular environment, accessibility and rapid movement of people are critical for equal development amongst island communities with different connotations (Varakantham et al., 2017; Moreno-Monroy et al., 2018; Coni et al., 2020). Indeed, as underlined by Chlomoudis et al. (2011), "*the notion of 'insularity' encompasses not only a geographic condition that pertains to a multitude of islands, but it also reflects a series of other social and demographic characteristics that stem from this geographic particularity*". In these contexts, Karampela et al. (2014) noted that transport is a key factor in island development and that connections within the island system "*not only concern the level of established linkages but also relate to the extent of accessibility and communications under the constraints of scale economies, micro-climate, and spatial reach of networks*". Furthermore, several strategic projects on the use of digital technologies for the development of insular PTSs enabled different administrations to make choices calibrated to the existing and specific problems of each island and subsequently improve the territory by creating strategies for growth and transformation from a place-based organisational and management perspective (Dameri, 2013; Ho, 2017; Gupta et al., 2019; Heaton et al., 2019). In this regard, the European Union's Strategic Plan 2020-2024 for Mobility and Transport establishes that the various governments should first collaborate with other interested parties to promote and strengthen sustainable public and collective transport services through interconnection with other modes of transport, such as "*active mobility (walking, cycling) as the backbone of urban mobility Governments need to be encouraged by all stakeholders to work more methodically*" (European Commission, 2020, p. 12). Also, the Smart Islands Projects and Strategies (2016) establishes the government priority of an island as "*its ability to implement integrated solutions to the management of infrastructures*" (p.1). Island policies "*should consider a large scale and long-term investment in public transport which attempts to provide a wider choice of modes, as well as a comfortable, convenient, reliable, and attractive alternative to the private car*" (Ibrahim, 2003, p.206). With these goals in mind, various governments and organisations have implemented accessibility policies based on the concept of a smart island in conjunction with strategic initiatives to enhance internal public transportation services via digital technologies and innovative data. Indeed, the smart island is seen as a region in which the island's uniqueness might trigger beneficial processes to foster a sustainable local economy and a good standard of living via the use of ICT. Considering the example of Curaçao (Kingdom of the Netherlands), Goede (2018) states that it is required "*to reform the public transport system to increase the level of mobility of the population*" (p.154). Singapore administrators also see integrated and continuous multimodal public transport as the backbone of its land transport system (Lam et al., 2006). Singapore has been involved for years in a technological innovation project that includes various areas of island development (Smart Nation Singapore, 2022). Yadav et al. (2017) stress the need to integrate "*sophisticated information and communication technologies (ICT) with traditional urban infrastructure together with the participation of various stakeholders to create a more equitable and sustainable system*" (p.1249). In this regard, Soomauroo et al. (2020) argue that "*islands typically have high energy costs, due to a lack of economies of scales and expensive fuel costs resulting from their insularity and remoteness*" (p.7). They underline the need for facilitators of sustainable transport that identify an electric fleet to have not only important environmental and economic benefits, but also multimodality in order to obtain less carbon-intensive mobility models. Arneodo et al. (2017) highlight how the smart mobility service has to consider a new and integrated approach to strategic planning and, in parallel, the development of different technological components (Abis et al., 2016; Torrisi et al., 2020; Garau et al., 2021; Pellicelli et al., 2022; Torrisi et al., 2021). The implementation of the mobility service would serve to facilitate "*citizen's life during their travels across the Region or improving their awareness of all the offering mobility possibilities using specific info mobility services*" and also to "*improve the control and management capability over the whole regional mobility*" (Arneodo et al., 2017, p. 1). In this regard, Mantero (2022), focusing on the socio-territorial dynamics of six European islands, underlines the need for "*changing people's approach to distances and accessibility, introducing and promoting new lifestyles, a new concept of time, new social relationships, more new habits and behaviours in general*" (p.5).

In the last ten years, the approach to accessibility has significantly changed thanks to digital solutions and information systems that have facilitated more sustainable mobility alternatives, as well as the development of indicators, multimodal platforms and applications able to combine different transport modalities (Melkonyan et al., 2020; Carra et al., 2022). However, a feasible project based on real data and underlying problems correlated with insularity is still lacking in the literature. Specifically, there is a lack of intermodal spatial planning for islands that is capable (i) of enhancing shared mobility for areas with low demand and, therefore (ii) of reducing the gap between weak internal areas (rural contexts with low density and high depopulation rate) and strong coastal ones and, (iii) of reducing the gap between low-quality shared public transport and unsustainable individual private transport, by considering the existing infrastructure.

To fill these gaps in the scientific literature on island contexts, the study's main aim is to develop an accessible spatial planning approach, combining PTS and rental services with the driver, by considering the principles and problems of island contexts. To accomplish this, the paper begins with a theoretical study that connects the principles of insularity and territorial accessibility (section 2), and then the paper focuses on the case study of Sardinia (section 3), particularly emblematic not only because it is an island context but also because, over the years, its geographical configuration has led to a transport system that favours coastal areas, creating a strong socio-economic gap in the hinterland. Section 4 describes the methodology for conducting spatial analysis based on the most recent available data on origin-destination mobility combined with real data using the Kriging method. Section 5 applies the methodology to the case study region, emphasising the articulation of homogenous zones that need intervention and providing a new territorial proposal. Finally, the results are discussed, as well as the research's future directions (section 6).

2. The principles of insularity and accessibility: state of the art

The accessibility in and for the islands is not a new problem. However, a review of the literature reveals that mobility and accessibility solutions in island cities remain inadequate and unsuitable for the increase of public road transport during the summer season, when the islands are exposed to higher stress (Zhou et al., 2011; Sudiarta, 2013; Luis, 2015; Smart Island Italia, 2022) and that, until recently, mobility planning is based on a logic of private transport (Bakogiannis et al., 2018). Ibrahim (2003) stresses the importance of implementing solutions that encourage the use of public transport by limiting the use of cars. He also highlights how, in an island context and with a limited land supply, it is not enough to improve public transport modes, but it is necessary to "*enhancement of all intermediate and end-point facilities, such as linkways, customer service and service information*" (Ibrahim, 2003, p.1). Mateu et al. (2017) note how the promotion of transport infrastructures and mobility policies are essential both for lowering regional disparities and providing access to the island and peripheral regions, and for the economic, social, and territorial development of the whole island. They also add as "*it is important to recognise the increase in accessibility and connectivity from the islands ushers in new formulas to export products and strategies to promote research and innovation policies*" (Mateu et al., 2017, p.56). Therefore, the mobility sector acquires fundamental importance in the socio-economic development of an island context. Thus, transport planning must consider the diversity of island spatialities and centre-periphery relationships (Grydehøj et al., 2019). Grydehøj et al. (2019) highlight how the improvement of connectivity must start from the specificities of an island because there is no single solution as island communities face various challenges. In this regard, Monfort (2009) also argues that each island is characterised by its insularity and political and socio-economic specificities and that these must be the basis for planning island mobility. However, Garau et al. (2019) find several structural problems prevalent in various island contexts. Most of these problems are due to inadequate infrastructure design, especially in the larger islands or island regions. In essence, they are related to the increased expense of sea and air transport, communications and infrastructure as a result of natural and climatic constraints, limited useable land, and barriers to access to school and health services (Garau et al., 2019b). Thus, it is significant to emphasise a key distinction between islands for the purposes of this study: medium and small islands (small islands that are part of archipelagos and have a limited area of land) and large islands (which are Nations or island regions).

The first ones have regulated transport planning, by following specific strategic goals through the Sustainable Island Mobility Plan (SIMP). These specific objectives (Tab. 1) are aimed at problems caused by insularity, such as 1) guaranteeing a minimum level of accessibility to the main destinations[1]; 2) guaranteeing services for all citizens and 3) building a transport system that contributes to the financial, social and environmental sustainability of an island (Sustainable Island Mobility Plan, 2017).

Tab. 1
Strategic goals of a SIMP reworked by the authors.

Strategic goals of a SIMP
1) Guaranteeing a minimum level of accessibility to the main destinations
Improved safety and security across the whole island road network and overall transportation system.
Logistics chain optimisation
High-quality and more accessible public transport (ICT use, on-demand service provision, etc.)
Improving air and/or sea transportation (from/to and around the island)
2) Guaranteeing services for all citizens
The re-allocation of public space and the restriction of traffic access and parking
Stimulating car-free vacation destinations
New ways of using the car (e.g., car-sharing, car-pooling, etc.)
Optimising the design of multi-modal hubs and terminals
3) Building a transport system that contributes to the financial, social and environmental sustainability of an island
Promoting car-sharing, car-pooling, bike sharing and other forms of sharing economy
Efficient management of the seasonal peak of travel and parking demand and reduction of the subsequent air and noise pollution
Stimulating projects at the nexus of mobility and energy, such as electromobility, to promote alternative fuels and the smartening of the island electrical grids
A significant change in the modal split towards sustainable transport modes
Promoting walking and cycling (creating a comprehensive pedestrian and cycle network, restoration of hiking trails, bike-sharing, etc.)
Intelligent transport management and information systems (ITS), on-demand service provision, ICT use, etc., integrating the existing and new mobility services.

Source http://www.scottish-islands-federation.co.uk/wp-content/uploads/2017/11/Smart-Islands-Initiative-Sustainable-Island-Mobility-Plan.pdf

Table 1 shows how SIMPs are related to development goals related to sustainable and smart mobility. These goals are also valid for the major islands, which do not yet have a standard rule. However, for major islands (such as Sardinia in Italy), mobility planning becomes more complicated, both in the territorial context (where the extension establishes a clear distinction between inland and coastal areas despite its precise boundaries) and in the social realm (where demographics and inclusion are inextricably linked to the island's transportation system). Therefore, this leads to reflect on two accessibility principles related to the major islands and strongly connected to the insularity and accessibility concepts and to the structural problems of the major islands: (i) equity, cooperation between areas and geography of the place and (ii) population distribution and social inclusion. These two principles are briefly described below.

(i) Equity, cooperation between areas and geography of the place. Numerous studies have revealed that the island territory's internal constraints manifest themselves, in most cases, in a distinct division between interior and coastal zones (Cross et al., 1999). Indeed, the inland areas of the islands contain undeveloped territorial capital, and social-economic decline that is caused by a lack of essential services and of the social costs associated with production and consumption processes (National Strategy for Internal Areas, 2022). In this regard, the already-tested smart island projects (Chatzimpiros, 2013; C 268/8, 2015; Boletín Oficial Del Estado, 2015; Smart Islands Projects and Strategies, 2016; Smart Islands Declaration, 2018) provide a cross-sectoral strategy for the whole territory to achieve balanced development across diverse social and economic sectors (inland, coastal areas). Within the Smart Island paradigm, balanced growth of an island system begins with the concept of air, sea, and, most importantly, land accessibility. This latter is defined as the ease with which a place can be reached via optimal modes of transport (Moreno-Monroy et al., 2018; Coni et al., 2020), and it becomes the primary factor in increasing connectivity in a territory with a limited extension due to its geographical structure. Thus, the inherent qualities of an island, such as its small size, isolation from high-altitude environments, and social and demographic factors, should serve as a starting point for establishing infrastructure links.

(ii) Population distribution and social inclusion. Island accessibility projects that have shown to be more efficient over time are connected not only to the quality of the transportation infrastructure and the physical configuration of the territory but also to the territorial organisation based on population distribution. Indeed, as the Treaty on the Functioning of the European Union (TFEU, art.174) demonstrates, one of the major disadvantages of island regions is demographic decline, which culminates in an ever-increasing depopulation of rural and inaccessible areas (C 326/4, 2012; European Commission, 2022b). According to the European Commission, this is due to rural residents' inadequate access to health care, education, employment, and other services (Velaga et al., 2012; Gogola et al., 2018). Additionally, as highlighted in the Interreg report (2018), these areas depend on offered transportation services or infrastructure, and transport with spatial integration goals plays a key role in social inclusion, particularly for rural areas and communities (Gogola et al., 2018). As a result, it becomes vital to develop a network of smart strategies that can be applied over the whole island area to improve mobility (Bansal et al., 2015). Consequently, it is vital to support initiatives in certain areas of regional development through information systems and data digitalisation, which are beneficial for comprehending the dynamics of the society in a specific area (Zamperlin et al., 2017; Chiordi et al., 2022). With these premises in mind, the purpose of this paper is to provide a smarter, safer, and more sustainable vision of PTS in island

[1] In this study, the authors consider the accessibility as the ability to reach a place. Indeed, it is of relevance the possibility to access easily to the main destinations because the Sardinia is the third largest Italian Region. However, owing to low population w.r.t. other regions, its infrastructure network is old and does not help reach all destination quickly. Therefore, improving the access, by e.g., improving exiting connections, the road network with paths adjustments, providing higher coordination among several PT would expect to increase the accessibility.

settings, with a particular emphasis on how the internal characteristics of islands can serve as a basis for designing or implementing projects related to the island's smart accessibility. The innovation proposed by the authors is centred on the concept of an intermodal network that serves as a focal point for cross-sector cohesion, through managing infrastructure and the island's comprehensive transportation system. This seems crucial because an island cannot host many infrastructure hubs. Also, considering the territory's limitation and geographic location bordered by the sea, efficiency is required in regions considered more sensitive and bothersome (such as interior areas), as well as the usage of information and communication technologies (ICT). To accomplish this, the case study of Sardinia will be analysed, as it is particularly emblematic in the field of public transport because management policies in the internal areas resulted in "*the stagnation, degrowth, and development of the Inner Areas*" (National Strategy for Internal Areas, 2022, p. 14). Furthermore, the current PTS organisation in Sardinia does not consider some island specificities that should characterise the internal mobility strategic choices. This paper aims to cover the previous drawbacks.

3. The case study of Sardinia, Italy

As is the case with numerous European islands, the Sardinian Island system is divided between coastal areas with high daily traffic and inland areas with low service centralisation (Garau et al., 2020b; Garau et al., 2021). Together with a strong economic disparity between these centres, this results in demographic shrinkage and, more importantly, population ageing, to the point that depopulation estimates for many villages are alarming (Garau et al., 2020a). However, permeability between coastal and inland locations remains a challenge (Fig. 1) since structural interdependencies have not been activated to include inland areas in a functional qualifying viewpoint determined by economic, social, and infrastructure concerns (Regional Transport Plan, 2022; Sardinia mobility, 2022). For these reasons, it is essential to concentrate on situations involving the island's various regions to act effectively on public transportation.

Sardinian reality is characterised by a considerable part of the population that commutes every day from their town of residence to the island's most developed cities through, in most instances, a private automobile for employment, study, or other purposes. Indeed, compared to inhabitants of the island's main centres, which are supplied with all necessary services, residents of the smaller centres are obliged to travel every day, incurring extra travel time and financial resources. Fig. 2 shows how the modal imbalance is still relatively strong. Cars contribute for 65.2% of travel (48.3% for drivers and 16.9% for passengers) and have an occupancy coefficient of 1.35. Public transport represents 11.9% of journeys, of which 10.3% is by road and 1.6% on train. Bicycling and walking accounted for 20.9% of travel.

As for travel times, 45.2% of these are between 7:15 am, and 8:15 am, and only 6.5% of travel is after 9:15 am. 71% is before 8:15 am. Over 60% takes place in short times, less than 15′, while over 85.9% of trips are less than 30′ (Tab. 2a).

Additionally, the gender structure of the resident population is characterised by a higher proportion of females than that of the mobility structure. Males make 55.35% of the trips, while females make 44.65%. 98 travels to study/work for every 100 male inhabitants, but only 76 for every 100 female residents (Tab. 2b).

However, still today not only the "*evaluations are extremely negative on some crucial dimensions such as infrastructures*" (Amenta et al., 2020, p.5) but, considering the words that Chlomoudis et al. (2011) use to describe mobility in Greece, PTSs highlight some weaknesses caused by "*a generic (non-focussed) and static (non-evolving) approach*" (p.3). In Sardinia, a generic unfocused approach can be considered because the PTS territorial organisation does not consider individual municipal problems in terms of accessibility to transport, orography, and the relationship between populations (Coni et al., 2020) On the other hand, the non-evolutionary static approach of the public transport system is a result of the lack of integration of infrastructures with the evolution of the specificities of some areas in terms of demographic changes, commuting, and economic and social well-being (Coni et al., 2020). Indeed, Sardinia is characterised by the presence of stronger areas

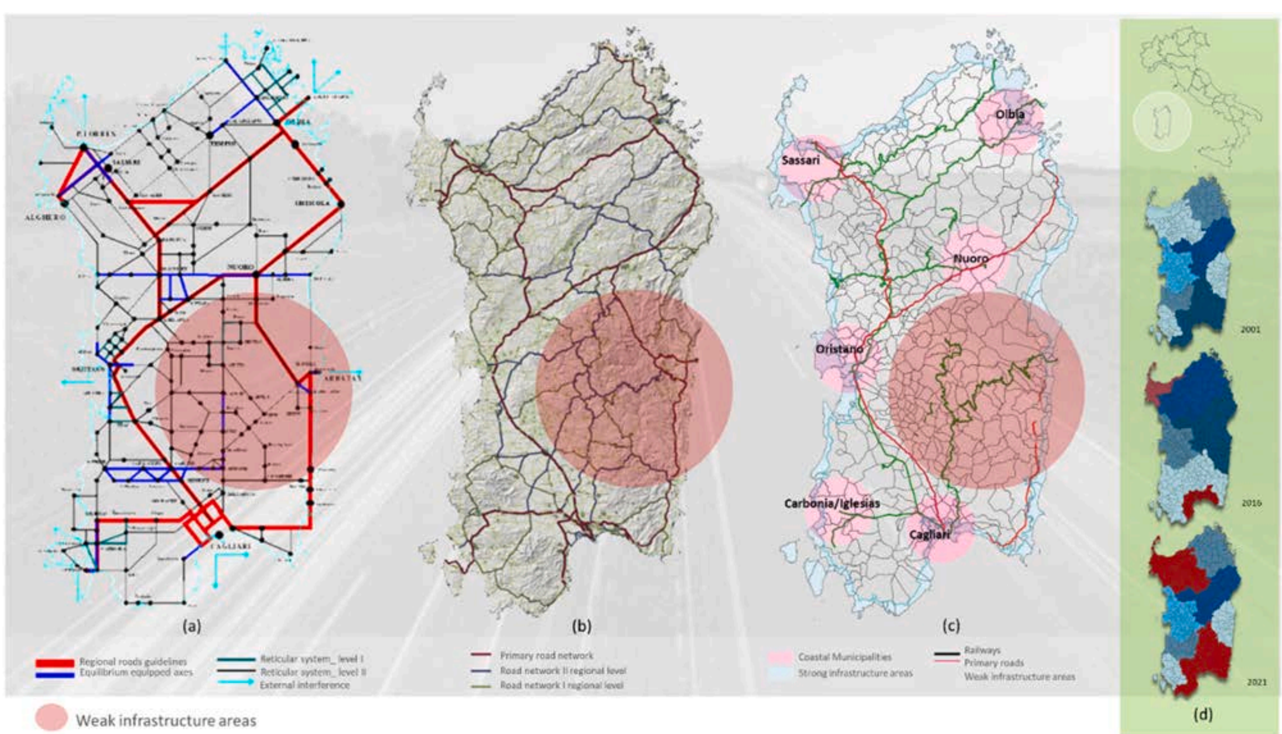
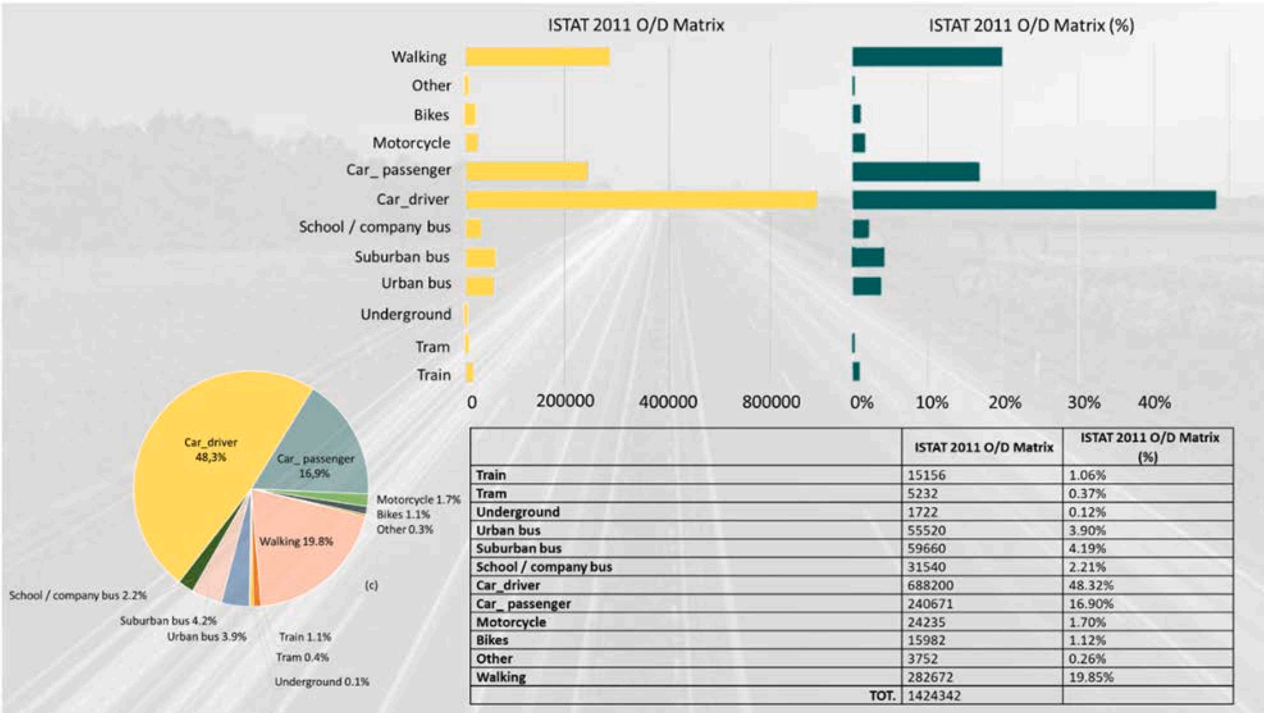


Fig. 1. Permeability in Sardinia. Structure of the hubs Region-City (a) and main network (b) Source: Regional Transport Plan (http://www.regione.sardegna.it/documenti/1_13_20081211102551.pdf). Accessibility study (c) and subdivision into provinces (d) Source: authors' elaboration.

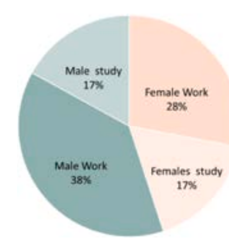


	ISTAT 2011 O/D Matrix	ISTAT 2011 O/D Matrix (%)
Train	15156	1.06%
Tram	5232	0.37%
Underground	1722	0.12%
Urban bus	55520	3.90%
Suburban bus	59660	4.19%
School / company bus	31540	2.21%
Car_driver	688200	48.32%
Car_ passenger	240671	16.90%
Motorcycle	24235	1.70%
Bikes	15982	1.12%
Other	3752	0.26%
Walking	282672	19.85%
TOT.	1424342	

Fig. 2. Distribution by means. Source: authors' elaboration from ISTAT 2011 (https://www.istat.it/it/archivio/139381)

Tab. 2
(a) Relationship between gender structure and mobility. Source: authors' elaboration from ISTAT 2011; (b) Travel times. Source: authors' elaboration from ISTAT 2011

a) Relationship between gender structure and mobility			
Mobility gender breakdown study/work		Population gender breakdown	
Male study/work movements	Female study/work movements	Population 2011 (male)	Population 2011 (Female)
55,35%	44,65%	48,88%	51,12%
b) Travel times			
H > 7:15'	25.8%	>15'	60.6%
H 7:15' -8:15'	45.2%	15' - 30'	25.3%
H 8:15' -9:15'	22.6%	30' – 60'	10.8%
H > 9:15'	6.5%	60'	3.3%



within the island system that "*highlight a spontaneous creation (elaborated from population movements) to groupings of municipalities (of homogeneous areas)*" (Garau et al., 2019b, p. 18).

These locations, almost all of which are located around the coasts, are popular for daily commuting because they provide superior services that encourage residents of nearby towns to commute daily for work, secondary education, or health care. Furthermore, during the summer, these centralities are strengthened as beach tourist destinations. Indeed, tourist demand in Sardinia is disproportionately centred along the coast, bypassing the potential of the interior regions. This causes a strong impact on the transport sector, because, due to the shortcomings of public transport, both in terms of infrastructure and organisation, over 92% of tourists travel by private car. A broader vision of the territory would therefore be needed, tending to integrate vocational and structural diversities to contribute to developing the weakest areas, through a rational organisation of infrastructures. To do this, the authors provide an analysis criterion for restructuring a new, smarter, safer and more sustainable structure than PTS through a place-based organisation. The purpose is to implement a physical structure of the road network and functional services to ensure PTS accessibility to the territories, at least during the main daily rush hours.

4. Methods

The focus of this section is the definition of a methodological approach capable of comparing the geography of the place and the local public transport system through the analysis of the dynamics of mobility in Sardinia.

Sardinia has 377 municipalities, among which only two cities exceed 100,000 inhabitants (Cagliari and Sassari) and two more than 50,000 (Quartu Sant'Elena and Olbia). Of the remaining 374 municipalities, only 24 exceed 10,000 (Istat Sardinia, 2021). The Sardinian spatial population distribution produces a regional system characterised by coastal strategic polarities to the disadvantage of inland regions. This has been aggravated throughout time by the absence of appropriate multipolar mobility linkages, which has emphasised the gap between strong and weak polarities (Garau et al., 2019b; Garau et al., 2020a). These premises are essential to understanding how to apply an approach able to compare the geography of the place and the local public transport system through the analysis of the dynamics of mobility.

The proposed method is organised into three main steps, as shown in Fig. 3:

Step 1) Supply and Demand mobility data collection;
Step 2) Analysis of supply and demand data;
Step 3) Proposal of a revised PTS network.

Each step is synthetically summarised for the main points in what follows.

4.1. Supply and demand mobility data collection

In step 1), supply and demand data should be gathered from several sources.

As for supply data, these data mainly include route path, bus stop/station locations, and frequencies. These data refer to the main transport modes available in Sardinia, i.e., trains and buses and are gathered from shape files provided by the region Sardinia which funds the extra-urban and urban transport into the island.

As for demand data, these data mainly included OD trips using the PT network and were collected from the National Institute of Statistics (ISTAT) and refined with vehicular counting data collected from the massive road network sensors located in the metropolitan area of Cagliari.

4.2. Analysis of supply and demand mobility data

In step 2), the processing and analysis of supply and mobility data follows.

As for supply data, in Sardinia, there are two different PT infrastructures: road network and rail network. Both infrastructures were adopted to enable extra-urban and urban networks, as indicated in Fig 4.

As for the extra-urban rail network (shown in black in Fig. 4), the rail network mainly links the south of the island with the Northwest and Northeast areas. Moreover, most of the rail network is provided by ordinary-gauge state railways. In contrast, additional rail connections are supplied by narrow-gauge railways in the terminal parts of North (Sassari city) and South (Cagliari city) and were recently converted into the tram and tram-train systems, respectively.

Regarding the extra-urban road transport network, the PT in Sardinia is mainly managed by the regional company, called ARST, which handles about 70 percent of the total extra-urban network (in light blue in Fig. 4) using buses. Usually, buses offer services among several municipalities of the overall Sardinia within the reference Province (i.e., Metropolitan city of Cagliari, Sassari, Nuovo, Oristano, and South Sardinia). The remainder part of extra-urban transport is administered by 48 private operators (https://www.sardegnamobilita.it/homepage). These operators provide short, fragmented and disjointed routes. Conversely, as for urban transport, the four main centres (Cagliari, Sassari, Olbia and Nuoro, shown in green in Fig. 4) each have their own municipal network run by monopoly-holding local businesses.

Notably, the overall extra-urban PTS lacks frequency in many interior parts of the Sardinian Region, where a dense supply of very small operators offering Rent for Driving (RfD) services has evolved to address this problem. Moreover, the supply analysis showed that: (i) the network was organised in a radial configuration a bit disregarding the concept of network; (ii) the overlapping of many operators resulted; (iii) a weak integration with the railway network is observed as well as a poor integration with sharing mobility and (iv) a widespread presence of RfD.

As for the demand mobility data, the authors choose Origin/Destination (O/D) matrices because they enable the identification of both the number of journeys originating from one municipality to another and the means or modes of transport used. In Sardinia's island system, which is divided into strong (coastal regions) and weak (inland areas) polarities, it is crucial to characterise transport demand by aggregating the individual movements that occur in the different polarities. Additionally, O/D matrices provide an instant glimpse of the number of people that use the current regional transport system's service throughout a certain time period. The O/D matrices are thus critical for understanding the inadequacies of a particular area of territory and the population's demands, particularly in an island system, which has clear territorial boundaries. This analysis was conducted based on the latest origin-destination matrices (O/D) surveyed in 2011 by the National Institute of Statistics (ISTAT) and updated in 2015 (Istat, 2011). These are the most recent national available data and remain for detail and structure one of the primary references for the analysis of mobility. The census survey included the assessment of origin-destination trips of the regional population for study and work reasons. Each trip is classified according to the type of vehicle used, the time and the time in which it takes place. Specifically, the analysis is based on 115,682 records[2] representative of 1,424,110 daily weekday trips, compared to the regional population, which in 2011 was equal to 1,639,362 (Fig. 5).

Fig. 5 shows how in 2011, the province with the greatest propensity to move was Cagliari, with 0.923 trips per inhabitant for study or work, while the province of Carbonia-Iglesias has the lowest index, equal to 0.784. Before proceeding with the analysis, it is necessary to consider that the data surveyed by ISTAT only concern the daily journeys for study and work, while there is no recording of movements for other reasons (health, leisure, family, etc.). Therefore, from the O/D matrices derives an underestimated mobility phenomenon compared to reality. Building a model based on real data is essential to fill this gap.

The city of Cagliari was chosen as a case study due to its importance as the island's primary tourist destination, with most daily entrances and departures and due to the relevant level of service quality in PTS achieved (Barabino et al., 2011; Barabino et al., 2013; Barabino, 2018; Garau et al., 2022; Annunziata et al., 2022). In addition, the sample of Cagliari is representative since about 29% of all regional travel takes place in this city. In particular, the daily entries in the city were compared with the values recorded by ISTAT (with the O/D matrices). The trend of the data detected by the sensors varies over months; therefore, an annual average value was used. Fig. 6 shows the sensor data and the values recorded by ISTAT. After quantifying incoming and outbound travel for Cagliari, the accessibility study was extended to a regional level using the Kriging method. As further detailed below, this method is used as planning support in the transportation sector because it facilitates the interpolation of a parameter in space while reducing mistakes (Ma et al., 2007). Specifically, in the literature, it is used to analyse geographical data to forecast travel demand (Miura, 2010; Gomes et al., 2016; Pinto et al., 2020) and for the analysis of origin-destination centrality (Linder et al., 2018; Lowry, 2014). Furthermore, the comparison of the surveyed movement to the real one with Kriging's method enables a higher degree of true connection at the regional level, minimising the error.

The 2011 ISTAT value of the inter-municipal attraction of Cagliari is 122,111. Considering an occupancy coefficient of 1.22 passengers[3] per vehicle, it is possible to compare the ISTAT census with the data from road monitoring. The comparison shows that the ISTAT data value is lower than the monitoring network value of 177,063 related to only cars

[2] These records represent a pair from an Origin (a municipality) to a Destination (another municipality) in the Island of Sardinia that recorded at least one trip.

[3] The ISTAT data bank provide the number of car trips distinguishing from drivers and passengers. Therefore, let P the number of passengers and D be the number of drivers (that also correspond to the number of cars). The coefficient of occupancy (Co) was computed by this formula: $Co = (P+D)/D$ that returned the value of 1.22 for the data at hand.

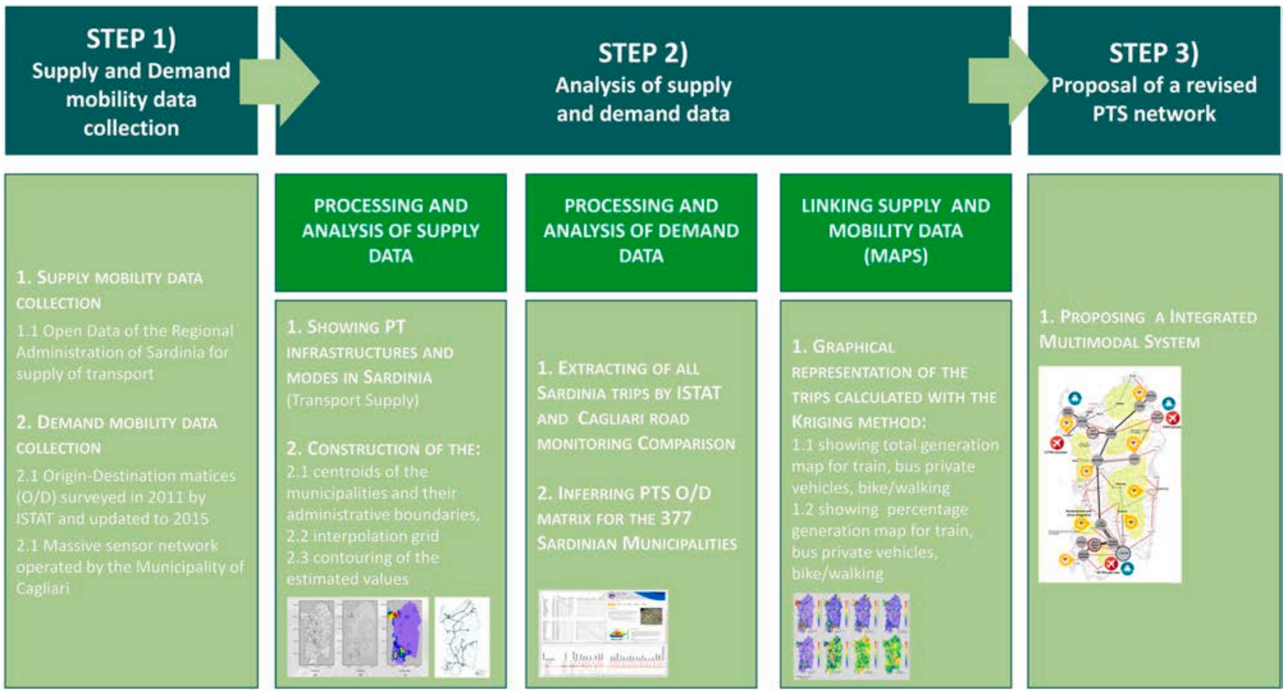


Fig. 3. Methodology steps

(number of drivers) for study and work purposes.

Specifically, these last data were gathered by the massive sensor network operated by the Municipality of Cagliari since 2008 with the aim of monitoring road traffic (Barabino et al., 2008; Tilocca et al., 2017). Specifically, vehicle data were collected by infrastructure-based sensors (i.e., loop detectors) placed on the main road network that enables the entry (exit) to Cagliari. Next, data collected on each vehicle are sent to the traffic management centre, by the communication network available in the specific location (e.g., optical fibre, GPRS). This centre presents the following macro activities:

1) monitoring of network state analysis by the received data;
2) management of actions to address the specific event (e.g., criteria and constraints to 'revise' traffic light plans);
3) management database to provide information on the traffic (including the information dissemination pre-trip and on-trip by WEB or Variable Message Sign) to the different operators that will be able to provide different services to the final users.

Therefore, vehicular data are adopted for other scopes than counting the vehicles only.

The disparity in comparison to data obtained from sensors on the ITS network is due to a variety of causes. The main determinant is the existence on the road network of trips for non-ISTAT-registered purposes (health care, tourism, leisure, handling of paperwork, etc.). Other reasons include the vehicular contribution made by unmonitored peripheral routes entering Cagliari. A further element of diversity is generated by the same definition of a cadenced shift in the typical day, which can vary according to the subjective interpretation of the interviewee subjected to the ISTAT 2011 survey. However, it is reasonable to assume (Sammer et al., 2012; Shen et al., 2019; Zannat et al., 2019) that these latter reasons have a limited impact and therefore the difference 177,063 - 122,111 = 54,952 equals to 31.04% is substantially attributable to other reasons for trip. Extending study/work mobility assessed by only ISTAT (with the O/D matrices) to a regional level led to overall mobility, which therefore includes other reasons, equal to 2,064,979 trips. Thus, a matrix was constructed and combined with all 377 Sardinian municipalities to compute the geographical distribution of trips.

Different indices were mapped using the geographic coordinates of each centroid C (x_c, y_c). Each centroid C behaves as both a trip generator/attractor with the other 376 municipalities of Sardinia. The generation of movement in each centroid (consisting of bus, train, private car, bike-foot) is represented by the absolute number of trips that leave C daily in different ways. The values distributed over the whole region were interpolated with the Surfer software on a regular grid of 1.0 km with the kriging method (Fig. 7).

Kriging is a regression method used in spatial analysis that enables the evaluation of a quantity, minimizing the mean square error. Kriging is a widely used and well-liked geostatistical interpolation method, mainly to its adaptability and accuracy in producing accurate maps for most data sets (Cressie, 1990; Wackernagel, 2003; Liu et al., 2020; Abdelhamid et al., 2022).

The value assigned to each node in the grid is determined by the values of nearby points, which are weighted according to their distance or other characteristics. The premise is that since the value investigated changes in space, points closer to one another are more comparable. The unknown value of a grid point was determined as follows. Specifically, let:

- V_a be the estimated value of the grid node;
- N be the number of nearby points used;
- V_i be the value in position i;
- W_i be assigned weight (where $\sum_{i=1}^{N} W_i = 1$)

V_a is computed as the weighted average of the known values as returned by eqn. [1]

$$V_a = \sum_{i=1}^{N} W_i V_i \tag{1}$$

A semivariogram is used to calculate the weights. The semivariogram is a graph that relates the relationship between the distance between two points $\boldsymbol{h}$ and the semivariance value $\gamma(\boldsymbol{h})$. It is defined as half of the mean square difference in values between two places separated by $\boldsymbol{h}$. Specifically, let:

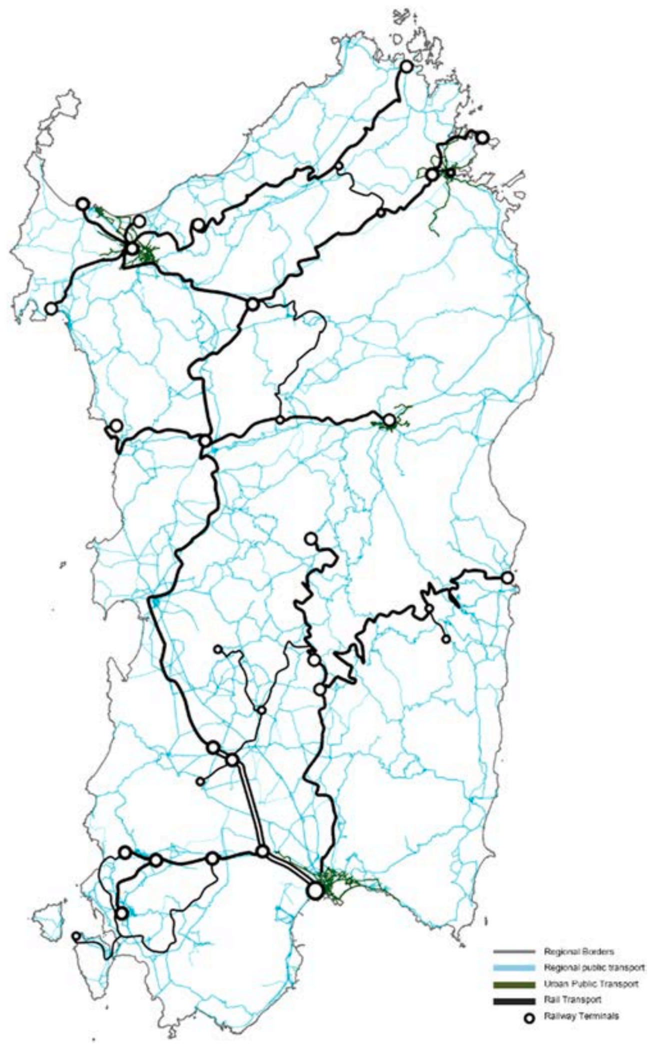


Fig. 4. PT infrastructures and modes in Sardinia (Transport Supply)

- $\gamma(h)$ be the estimated value considering node h
- Z be all the values assumed in the centroid xi
- xi be the centroid

$\gamma(h)$ is computed as returned by eqn. [2]

$$\gamma(h) = \frac{1}{2} Var[Z(x) - Z(x+h)] = \frac{1}{2N} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2 \tag{2}$$

Subsequently, the analysis was implemented through the Surfer 8.0 software. The input was the O/D matrix structured as shown in Fig. 8:

Once supply and demand data are analysed, a crucial issue is to build comprehensible and usable performance reports for e.g., planners, managers, decision makers (hereafter experts), for the effective analysis of data. In this context, a clear representation of the results can be done by maps. These maps are produced in a GIS environment and uploaded on a base city map. These maps show the opportunities and criticalities of public transport network according to the value returned by some indices and help experts detect those areas needing more attention to improve its PT performance.

The attraction maps are produced by interpolating the values from the 377 centroids in the direction of the considered centroid. Similarly, the generation maps were generated by interpolating the values from the considered centroid to the other 377 centroids. The values are georeferenced using the east and north coordinate values in the matrix's first two columns of Fig. 8.

4.3. Proposal of a revised PTS network

Finally, once criticalities have been detected, the last step builds to revise the PT network, as detailed better in the next section. Specifically, the main drivers to revise the PT network include: (i) the hierarchical network organisation; (ii) the integration among railway, PT, RfD and sharing mobility to provide more capillary and effective services; (iii) the reduction of the road congestion.

The overall methodology appears to be somewhat effective because it provides for the minimisation of calculation errors and graphical modelling of Sardinia's transport.

5. Results

This section shows the main result of the application of methodology (steps 2 and 3). Specifically, this section shows the graphical representation of the proposed methodology and the design hypothesis of the authors, based on an effective integrated multimodal model.

The proposed methodology enabled the development of several contouring systems differentiated by the purpose for the trip, mode of transport and time. Fig. 9 illustrates the maps created because of the data processing procedure. Specifically, the ISTAT statistics that distinguish the PTS were chosen and evaluated, namely those that travel through rail (Figs. 9 a, e) and urban bus (Figs. 9 b, f). Additionally, the authors wanted to study alternative modes of travel because of their close relationship to PTSs. In this regard, maps are created by considering also private car (Figs. 9 c, g) and transport on bicycle and on foot (Figs. 9 d, h).

Each representation of Fig. 9 has been scaled differently to emphasise the distributive structure and, therefore, has a different scale. By establishing an equal scale, the territorial peculiarities would have been eliminated.

The trips represented take place on public transport (train and bus), on private vehicles and by bikes and walking in absolute terms (Figs. 9 a, b, c, d) and as a percentage (Figs. 9 e, f, g, h). The scale of vehicle usage values from blue (minimum value) to red (maximum value). Fig. 9a shows the attitudes to rail travel, attributable to the presence of efficient service in the south-western and north-western sectors of the island. Although there is an important infrastructure that connects Sassari and the north-eastern part of the island, this infrastructure is not used. This also applies to public road transport (Fig.9b). Indeed, the population prefers to travel by private automobile, as seen in Fig. 9c with a more vivid blue, although the road network is more developed and better connected in the western part of the island.

This dynamic is much more evident in the percentage generation, which emphasises the link between railways (black line), roads (white line), and their usage, independent of whether (western and south-eastern bands) or not (north-eastern bands) a railway and road network exist. As previously stated, this is due to (i) the inefficiency of infrastructure networks and (ii) the absence of connectivity between infrastructure nodes and smaller communities in inland areas. Considering the lack of rapid and simple multimodality, existing PTS networks are underutilised. The comparison of the different maps enables making some observations. On the one hand, the total generation of the maps shown in Fig. 9 (a, b, c, d) demonstrates that the values for all modes of transport reflect the population distribution and presence of services in the island's coastal hubs, except for Nuoro. On the other hand, Nuoro is a hub for primary and secondary services essential to the region of central-eastern Sardinia. Between Nuoro and Cagliari, there is a substantial barrier to access due to the territory's morphology, which inevitably increases the gap between the coastal and interior regions, further isolating and making the hinterland inaccessible.

The widespread usage of private vehicles by the population reveals that the railway network is not branched, that it does not cover all sites on the island, particularly the north-eastern internal ones, and that it is poorly managed and difficult for day journeys. Interestingly the corridor

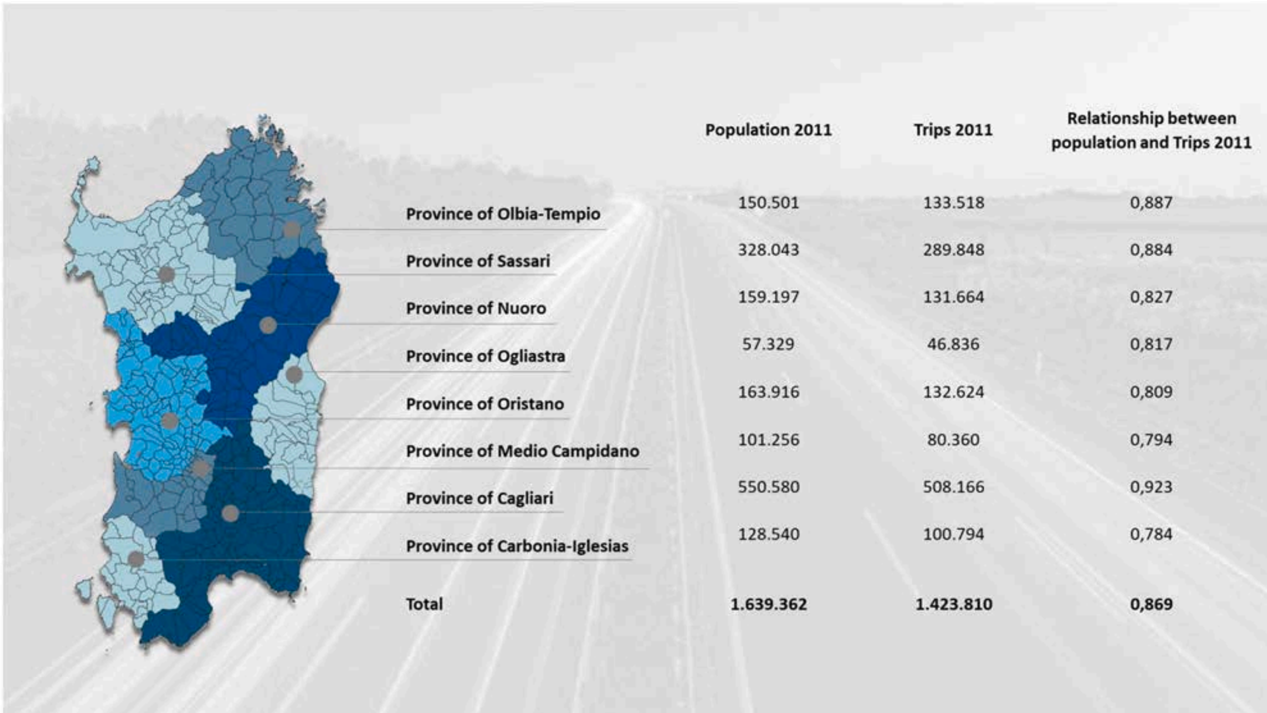


Fig. 5. Report on travel/population referred to the 8 Provinces of Sardinia in 2011. Colours represent the provincial boundaries

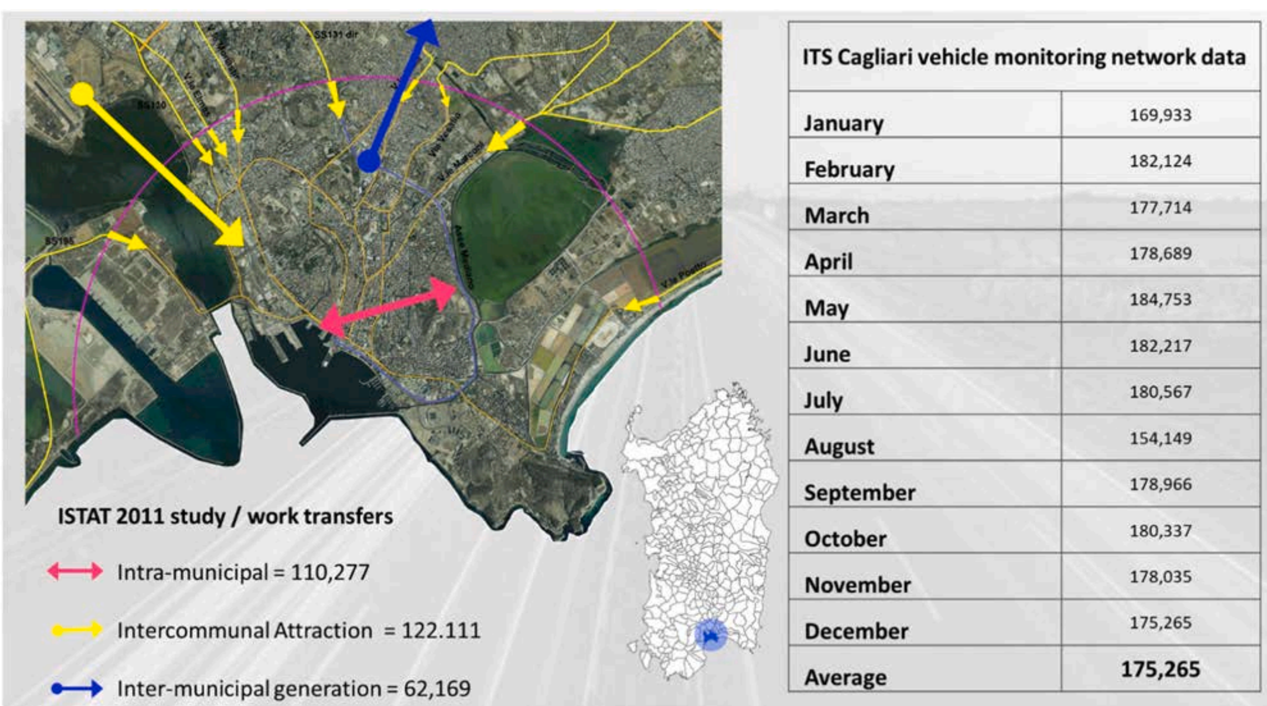


Fig. 6. Sensor data and values recorded by ISTAT 2011

from Oristano to Cagliari can be considered attractive owing to the employment of the new trains, which help guarantee a relative fast link to Cagliari. Conversely, Fig. 9a shows that the East part of the railway track is heavily underused with insignificant trips, as also expected owing to the large running times between Cagliari and Olbia, which are the main terminals. This evidence is critical because Olbia is the nearest port to the Italian mainland. Although slightly different, this dynamic is also evident in Fig. 9b for bus trips. Specifically, bus trips were concentrated from/to the municipalities that gravitate around the main Island centres, i.e., Cagliari, Sassari and Olbia, with an exception for Nuoro city (in green in the middle of Fig. 9b) and its surrounding municipalities. In contrast, a corridor of about 100km is adopted to satisfy bus trips from the south-westernmost part Sardinia. This evidence confirms that the island's whole PTS system falls short of customer satisfaction, thus most of trips were done by cars as also shown in Fig. 9c.

Fig. 9d describes the trips on foot and by bicycle. This map shows

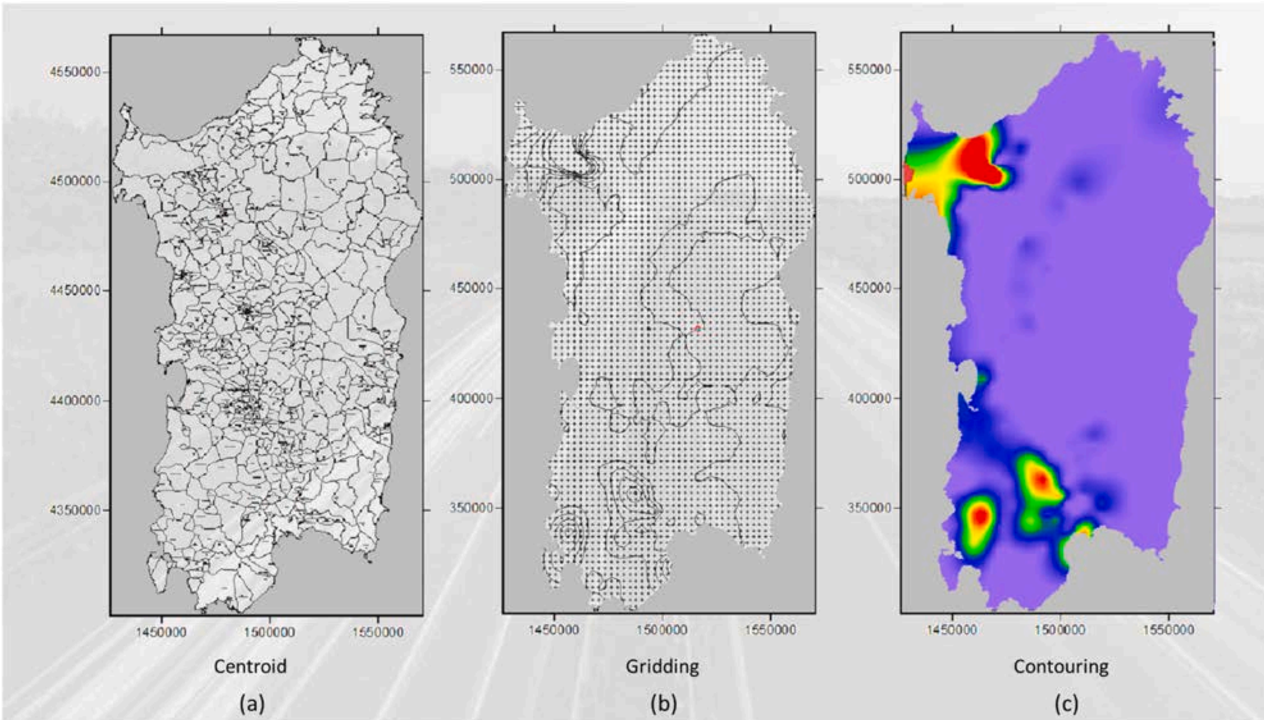


Fig. 7. (a) The centroids of the municipalities and their administrative boundaries, (b) the interpolation grid, (c) the contouring of the estimated values

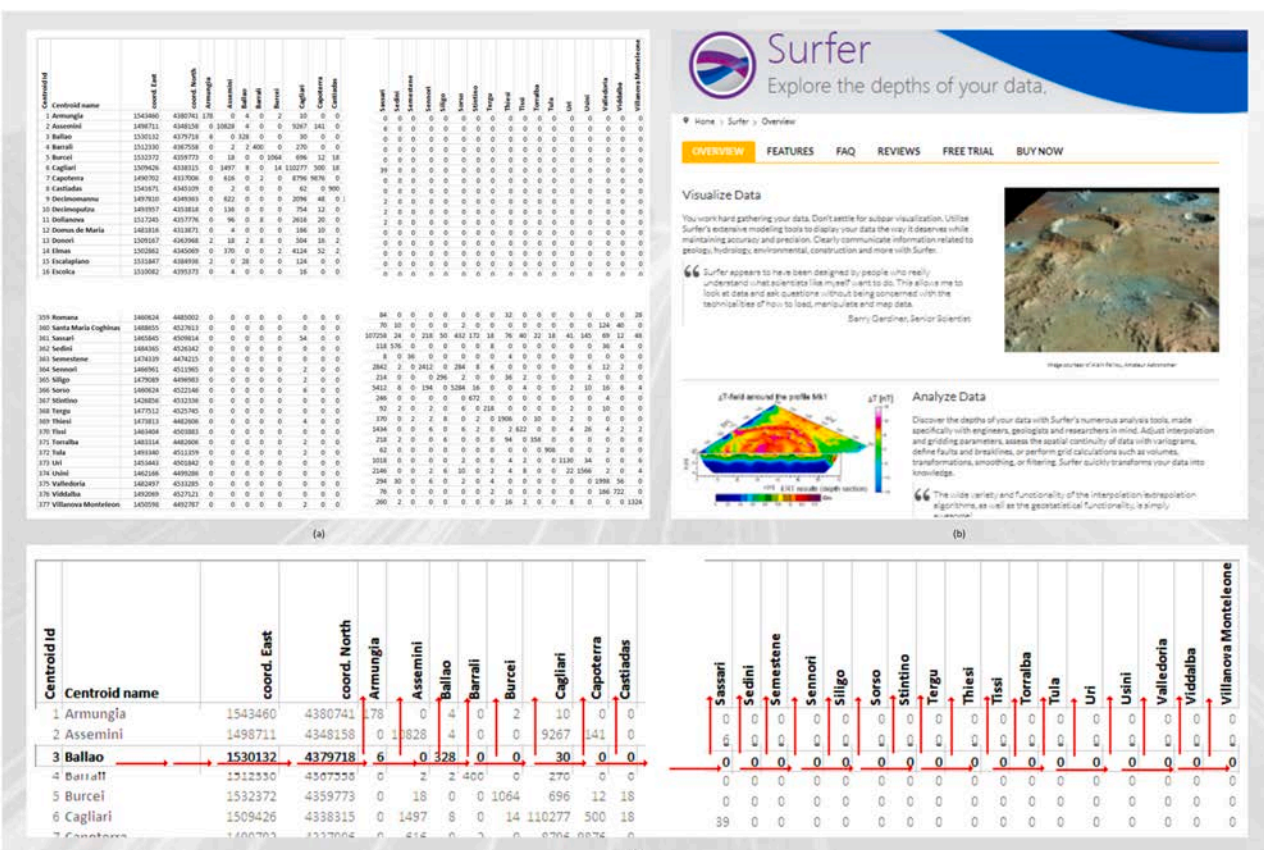


Fig. 8. Structure of the O/D matrix: (a) complete matrix; (b) an example (for centroid 3) of how the generation maps were estimated. The values of the centroid are distributed in the territory according to the degree of attraction of the other centroids; (c) a screenshot of the Surfer 8.0 software. Each entry of the matrix represents the number of trips from an Origin to a Destination

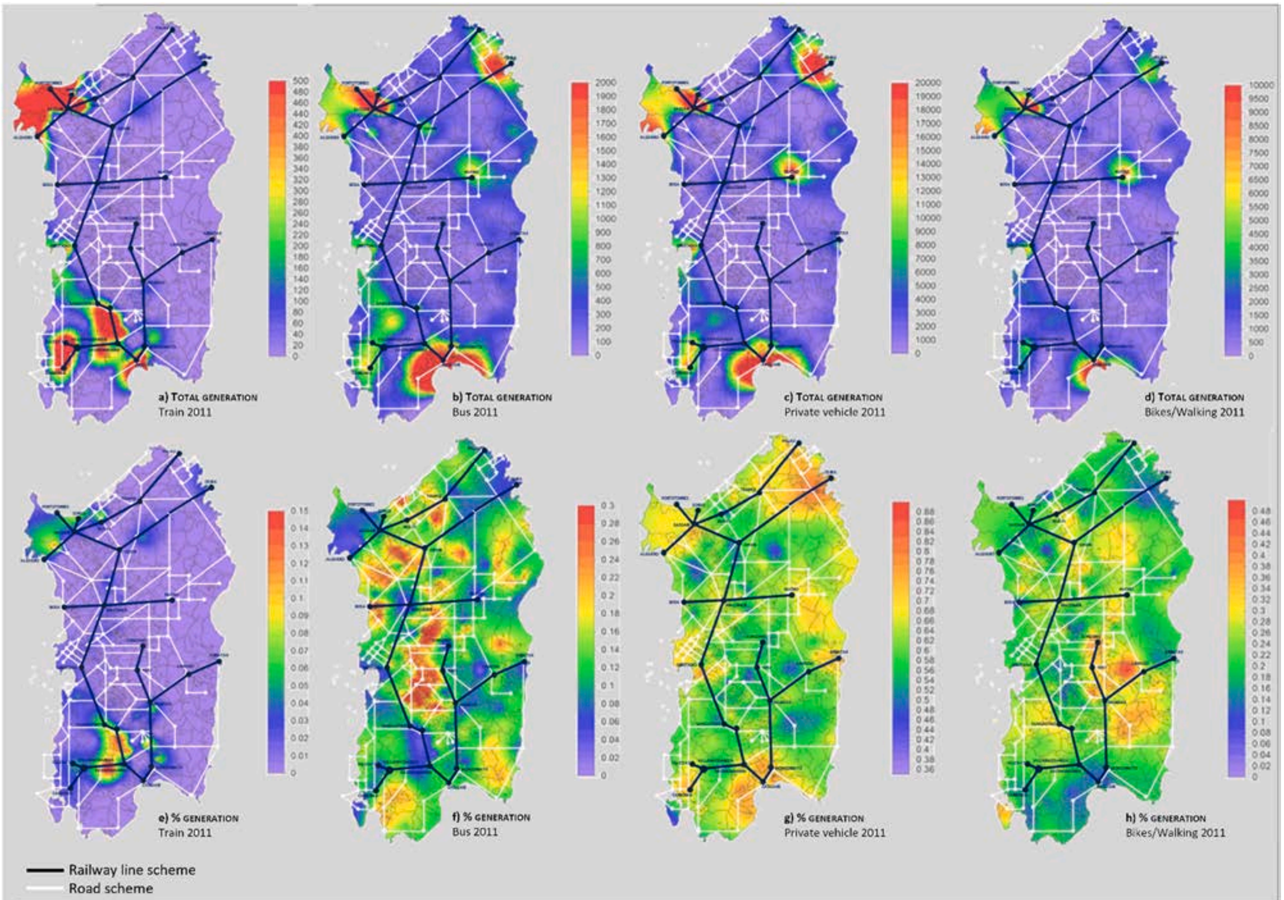


Fig. 9. Graphical representation of the trips calculated with the Kriging method in absolute terms (a, b, c, d) and as a percentage (e, f, g, h).

that this mode of transport is more prevalent in the largest metropolitan areas (Cagliari and Sassari), accounting for around 50% of total private traffic and having a fairly comparable distribution.

The next four maps (Figs. 9 e, f, g, and h) show the contouring values normalised to the total generation of each municipality. They enable communities to express their attitudes about a certain form of transport regardless of their population size. The region southwest of the island (Sulcis-Iglesiente and Campidano) has a high preference for trains (Fig. 9e). In the central part of the island and in the Oristano region, buses (Fig. 9f) are relevant in percentage terms. Private vehicles, bicycles, and walking continue to have comparable values to those calculated in total generation (Figs. 9 c, d).

The study reveals a total lack of accessibility networks across the island. There is a total absence of transport planning that organises the territory's mobility by prioritising links between weak and strong hubs, as well as between coastal regions and the hinterland, based on real population movements. This significantly intensifies the disparities across cities around the island. Additionally, the calculated values, as seen in Fig. 9, highlight some regions where real gaps exist in mobility planning (Fig. 10 in yellow). To address these issues, the authors suggest an intelligent transportation planning system for Sardinia based on an integrated multimodal system (Fig. 10) connecting PTS (train and bus), rental service with driver (RSD), and tourist railway lines.

Fig. 8 illustrates an articulated system that enables a more extensive network to be supported across the region and encourages more accessibility across the area using real data obtained using the Kriging method, location of ports and airports, and previously financed projects by the Region of Sardinia. This is accomplished by connecting the current network (train and bus) to a RSD, which would facilitate travel even in inner areas. Specifically, the integrated multimodal system proposed in Fig. 10 underlines:

(i) how to intervene in a more widespread way on the mobility network, in the areas with accessibility gaps (Fig. 10 in yellow). To do this, the project links a widespread RSD system to the railway network (green and black lines) and to public transport by road (red line).
(ii) how to favour a sustainable transport system by improving the network and, therefore, facilitating the use of public transport, to the detriment of private transport. The management of RSDs was designed in relation to the existing PTS and the need for connection between coastal areas and inland areas.
(iii) how to favour sustainable tourism because it designs easy and interconnected connections between main ports and airports and PTS / RSD. This would also enable in the summer months, of greater tourist intensity, to limit the use of private cars.

Additionally, this system would enable for the limitation and partial resolution of issues correlated to inner accessibility by promoting and supporting equitable access across the territory. Indeed, the project would (i) contribute to reducing the socio-economic gap between coastal areas and the hinterland, by establishing more structured and dynamic connections; (ii) facilitate the consideration of a more equitable distribution of primary and secondary services throughout the territory's urban, rural, and industrial sectors. The representations of real data (Fig. 9) and the link to existing and previously funded infrastructure (Fig. 10) also enable a feasible integration between the mobility plan and the island's growth plan based on population demands. This is significant in an island context where socioeconomic problems are inextricably tied to a structural configuration in which

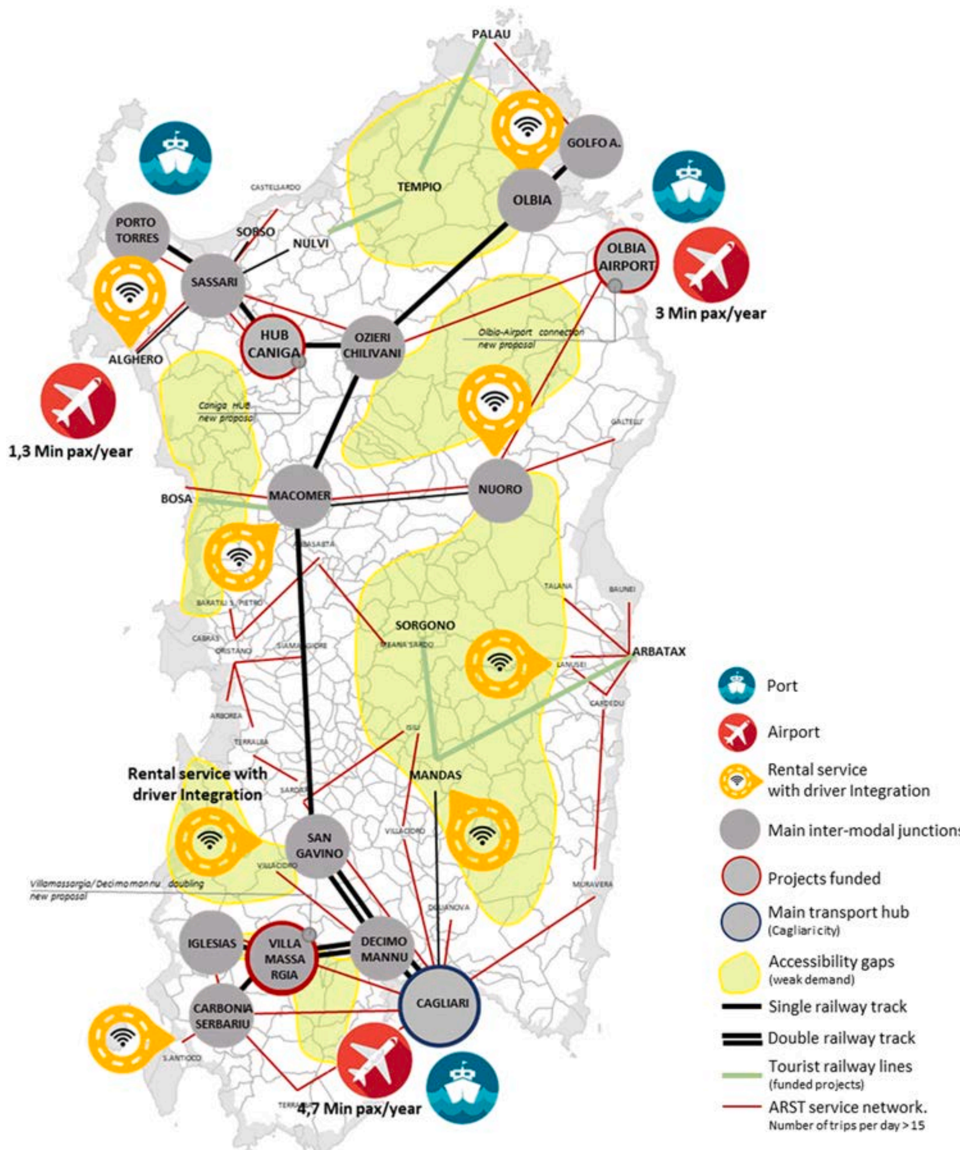


Fig. 10. Proposal of the integrated multimodal system

planning tools do not communicate with one another.

6. Conclusions

Sardinia has developed a weak public transport service (PTS) structure because of urbanisation and low population density, resulting in excessive dependence on private cars. Proof of this is that almost all people who travel to the island for work and tourism use a car. In addition, the infrastructural network and PTSs were developed in a disconnected way concerning settlement dynamics.

The spatial interpretation through the study of mobility provides a comprehensive picture of the uses and needs of the population. The trip analysis reveals that the permeability between coastal and inland areas remains challenging, confirming that the multipolar regional system is strongly centred on coastal zones. The strong need for inhabitants to transit between municipalities (for a variety of reasons, mostly connected to the presence of island services) produces a dynamic that the public transportation system cannot sustain. Indeed, in comparison to the advantages of the residents in the island's larger centres, which are equipped with all necessary services, residents of the island's smaller centres are compelled to daily mobility through the commitment of additional time and resources in the island's centres of attraction. This triggers a regional mobility dynamic, which leads the resident population to smaller centres to move and, therefore to increase internal imbalances.

In other words, the modalities and opportunities for moving do not yet reflect Sardinia's socio-physical and socio-economic reality, which is marked by significant daily dynamism. Indeed, analyses indicate that the PTS in Sardinia cannot satisfy the real population distribution, which is also spread throughout several small, very low-density villages. The inner areas are rapidly depopulating, whereas the main cities on the coast are rising in population.

This study and the related analyses demonstrate the divergence between current reality and current trends (lifestyles and mobility, consumption, and pollution reduction in the transport sector), as well as how much the road infrastructure has developed over the decades, favouring almost exclusively private mobility.

This heavy reliance on private automobiles (Fig.9c) at the expense of public transport (Fig. 9b) is driven by a variety of variables, including service quality, lack of connectivity, distance to and from stations, and distance to/from homework. To overcome these gaps, this study examined the state of the art in Sardinia in terms of accessibility using statistical and real-world data, and then reforming the Public Transport Mobility system with the objective of enhancing accessibility. The reformation of Public Transportation Mobility was based on a comprehensive understanding of mobility's features, including the intensity of flows, trip times and durations, origins and destinations, modes of transport utilised, and motivations.

The main objective of the integrated train/bus/rental service with a driver (RSD) system is to consider the PTS as a valid alternative to private vehicles by identifying a network that optimizes the available resources. The transport continuity solution of this research (Fig. 10) enables the whole island system, and therefore all polarities (weak and strong) to create a daily, more sustainable and smart relationship for Sardinia.

This study contributed to the literature as follows:

- It has proposed a methodology able to fill the large scientific gap in mobility regional planning based on real data and underlying problems related to insularity (e.g. the gap between weak internal areas and strong coastal ones), by considering the existing infrastructure.
- It has offered a straightforward methodology that can identify and possible address similar problems in other insular and non-insular contexts by location-sensitive data.
- It has preliminarily identified a multimodal system capable of facilitating accessibility in isolated areas of the territory, such as mountainous or ultra-peripheral areas;
- It has considered the concept of smart mobility not linked only to technology (which becomes a tool used to improve and optimise transport planning) but as a concept that incorporates the consumer as a key component. In this sense, the integrated multimodal system proposed appears smart both (i) because it experiments with alternative forms of mobility connections, and (ii) because it proposes a mobility urban development project that encourages the use of public transport.

Specifically, this multimodal system may bridge the gap between shared public transport and unsustainable individual private transport. Relevant implications of this study are:

- The replicability of the methodology combined with location-sensitive data will enable to assess similar issues in other islands. Specifically, the results can be applied in similar contexts characterised by comparable elements such as a road network, transit system (e.g. number of routes and associated timetables), and travel demand. Conversely, the methodology implemented is general and, providing new input data which refers to the context at hand, the model can also be used for metropolitan areas where different types of PT modes will result.
- The high degree of applicability of this method is not strictly linked to PTS but can be generalised to other transportation modes.
- The island government can revise their policy and practice of transportation modes considering the findings of this study.

However, some project weaknesses need to be investigated. Indeed, in real life, the project would need close coordination between PTS and RSD managers. This cooperation should be active and proactive in essence, facilitating intermodal changes via an integrated management system that incorporates public and private sectors. Another critical element may be the project's execution and implementation. Even though the authors feel that accessibility is essential for growth in a vast island context such as Sardinia, integration with urban master plans could modify the project presented, increasing its efficiency. By using this methodology, there is a risk of not having a comprehensive understanding of the population's demands.

Nevertheless, these results are preliminary steps in the authors' agenda and raise several relevant topics for further research. This study provided a large and qualitative vision for the reorganisation of PTS in Sardinia. However, first, an overall transportation model should be implemented to check the overall technical feasibility. Second, a preliminary cost-benefit analysis or multicriteria method should be implemented to assess its economic feasibility on the overall island. Furthermore, this study paves the way for the theoretical study on accessibility and its connection to smart mobility and transport justice, especially in contexts with particular geographical and structural problems, such as islands. These new evaluations are welcome in further studies.

Author Contributions

This paper is the result of the joint work of the authors. In particular, "Methods" and "Results" are written jointly by the authors. Chiara Garau wrote the "Introduction", Giulia Desogus wrote "The principles of insularity and accessibility: state of the art", Benedetto Barabino wrote "The case study of Sardinia, Italy", and Mauro Coni wrote the "Conclusions".

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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