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Multimodal Transport Modelling at a Macro Scale: an application to the Adriatic-Ionian (AI) region

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Abstract

Transport planning is increasingly required to address issues that extend beyond urban or regional boundaries, particularly in the European context and in relation to connectivity policies. Within this framework, macro-scale multimodal transport models represent a fundamental tool to support decision-making processes, assess infrastructure performance and analyse the impacts of transport policies. This thesis focuses on the Adriatic–Ionian Region within the framework of the EU Macro-Regional Strategy for the Adriatic–Ionian Region (EUSAIR) and presents the update and application of the EUSAIR Multimodal Transport Model (EMTM) to the 2023 base year. The first objective is to describe the methodology adopted for the development of the model, with particular attention to supply and demand modelling and assignment procedures for passenger and freight transport. The model update includes a revision of road and rail networks, as well as an update of socio-economic data and origin–destination matrices. The second objective is to analyse the performance of the transport system through a set of supranational indicators, with particular reference to modal split, connectivity and accessibility. Active and passive accessibility indicators are computed with respect to population and employment, allowing the identification of territorial disparities and the role of different transport modes. Accessibility share indicators are also introduced to assess the relative contribution of car, bus and rail transport to overall accessibility levels. The results highlight significant heterogeneity within the EUSAIR area, attributable to differences in socio-economic conditions and network performance. Road transport emerges as the dominant mode in most areas, while rail accessibility remains concentrated along major corridors and urban nodes. Overall, the thesis demonstrates the relevance of macro-scale multimodal transport models and their related indicators as analytical tools to support policy evaluation at the supranational level.

Keywords: multimodal transport modelling, macro-scale transport planning, EUSAIR, accessibility, connectivity

Abstract in lingua italiana

La pianificazione dei trasporti è chiamata ad affrontare questioni che vanno oltre i confini urbani o regionali, in particolare nel contesto europeo e in relazione alle politiche di connettività. In questo quadro, i modelli di trasporto multimodale a scala macro rappresentano uno strumento fondamentale per supportare i processi decisionali, valutare le prestazioni delle infrastrutture e analizzare gli impatti delle politiche di trasporto. Questa tesi si concentra sulla Regione Adriatico-Ionica nell'ambito della Strategia Macroregionale UE per la Regione Adriatico-Ionica (EUSAIR) e presenta l'aggiornamento e l'applicazione dell'EUSAIR Multimodal Transport Model (EMTM) all'anno base 2023. Il primo obiettivo è descrivere la metodologia adottata per lo sviluppo del modello, con particolare attenzione alla modellazione dell'offerta e della domanda e alle procedure di assegnazione per il trasporto passeggeri e merci. L'aggiornamento del modello include una revisione delle reti stradali e ferroviarie e l'aggiornamento dei dati socioeconomici e delle matrici origine-destinazione. Il secondo obiettivo è analizzare le prestazioni del sistema di trasporto attraverso un insieme di indicatori sovranazionali, con particolare riferimento al modal split, alla connettività e all'accessibilità. Vengono calcolati indicatori di accessibilità attiva e passiva rispetto alla popolazione e all'occupazione, consentendo di individuare le disparità territoriali e il ruolo delle diverse modalità di trasporto. Vengono inoltre introdotti indicatori di quota di accessibilità per valutare il contributo relativo di auto, bus e ferrovia ai livelli complessivi di accessibilità. I risultati evidenziano una significativa eterogeneità all'interno dell'area EUSAIR, riconducibile a differenze nelle condizioni socioeconomiche e nelle prestazioni della rete. Il trasporto stradale emerge come modalità dominante nella maggior parte delle aree, mentre l'accessibilità ferroviaria risulta concentrata lungo i principali corridoi e nei nodi urbani. Nel complesso, la tesi dimostra la rilevanza dei modelli macro di trasporto multimodale e dei relativi indicatori come strumenti analitici a supporto della valutazione delle politiche a livello sovranazionale.

Parole chiave: modellazione del trasporto multimodale, pianificazione dei trasporti, scala macro, EUSAIR, accessibilità, connettività

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Introduction

Transport planning can be applied across different territorial scales. At first glance, it is often associated with the urban level; however, it can also extend to regional, national and even supranational dimensions.

For the latter, a relevant example is provided by the Trans-European Transport Network (TEN-T). This network was designed to go beyond national planning approaches and promote a more integrated European perspective. The TEN-T aims to enhance multimodality for both passenger and freight flows, while improving connectivity among Member States. In the railway sector, for instance, it seeks to strengthen interoperability along international routes and ensure common performance and safety standards across the European Union.

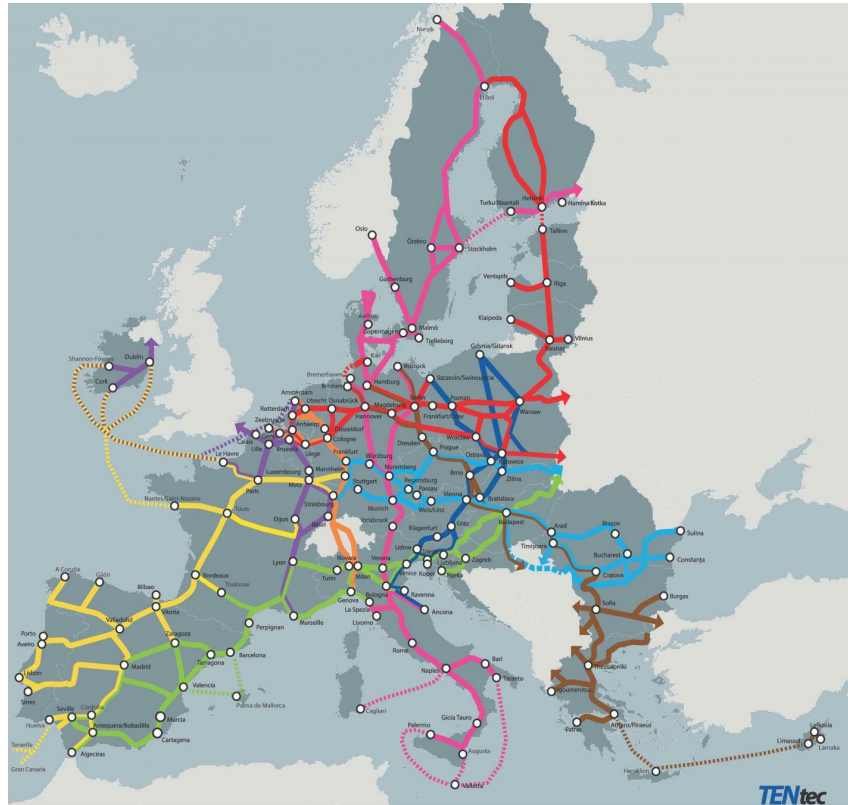


Figure 1: TEN-T Network and Urban Nodes [1]

In order to support the development of such policies and, more generally, the decision-making process, transport modelling has become increasingly relevant at the supranational level. From a modelling perspective, there is a growing need for tools capable of accurately representing both passenger and freight movements over large geographical areas. In this context, the integration of multimodal and intermodal aspects is essential to assess passenger and freight transport flows at inter-regional level and identify which infrastructures should be prioritised in order to ensure a more efficient and functional transport network.

One of the main challenges of multimodal transport models at the macro-regional or supranational scale lies in the extent of the study area and its intrinsic heterogeneity. Differences in territorial morphology, social and demographic characteristics and economic conditions significantly affect transport demand and must therefore be properly accounted for within the modelling framework.

At the European level, several multimodal transport models have been developed, differing in terms of applied methodologies and selected indicators. These models are commonly used to represent current transport systems and support policy evaluation by comparing reference scenarios with future scenarios that include infrastructure upgrades or changes in socio-economic conditions.

Another type of policy that has emerged at the European level in recent years is represented by macro-regional strategies, which focus on specific geographical areas that are particularly relevant with respect to certain shared challenges. In this context, within the framework of the EU Strategy for the Adriatic and Ionian Region (EUSAIR), the EUSAIR Multimodal Transport Model (EMTM) has been developed. This model represents the case study of application for this thesis.

This work has been carried out in collaboration with Tplan Consulting, a company based in Imola (Metropolitan City of Bologna), specialised in providing independent consultancy on transport infrastructure projects for both the public and private sectors.



Figure 2: Tplan Consulting

The thesis involves the first update of the EUSAIR Multimodal Transport Model (EMTM) to the new base year 2023, replacing the previous version based on 2017.

The objective of this thesis is to present the methodology adopted for the development of a macro-regional multimodal transport model and to analyse its results through a set of specific indicators, which may serve as a reference for similar modelling approaches at the supranational level.

The first chapter introduces EU enlargement policies towards the Western Balkans and discusses the role of transport strategies, with specific reference to EUSAIR. The second chapter presents the methodological framework of the transport model, describing its overall structure and main components, with particular attention to the supply, demand and assignment models used to represent transport flows within the study area. Finally, the third chapter provides a comprehensive review of supranational indicators for multimodal transport models, followed by the application of the proposed framework to the EUSAIR case study, including results and related analyses.

1 | EU Enlargement Policy towards the Western Balkans

Each year, the European Commission adopts the Enlargement Package, a set of documents outlining the European Union's enlargement policy [2]. Through this package, the Commission assesses the progress made by candidate countries and formulates conclusions and recommendations. Particular attention is given to the implementation of fundamental reforms and to the identification of clear priorities for future action in key areas such as the functioning of democratic institutions, economic governance, the ability to assume the obligations of EU membership, regional cooperation and good neighbourly relations.

For each Western Balkan candidate country, the Enlargement Package includes a dedicated country report in which the Commission provides a detailed assessment of progress achieved in the accession process.

EU enlargement policy is also closely linked to mobility and transport. In this field as well, regional cooperation plays a crucial role in ensuring strong transport infrastructure, networks and connectivity, which are essential for promoting economic and social growth in the Western Balkans and for strengthening the region's integration with the European Union. In this context, the extension of the TEN-T core network corridors to the Western Balkans represents a key priority.

In particular, following the adoption of the TEN-T and Connecting Europe Facility (CEF) Regulations in 2014, the *Orient East Med* Corridor was established, now referred to as the *Western Balkans–Eastern Mediterranean* Corridor. This development is supported by EU financial instruments such as the Western Balkans Investment Framework (WBIF), which provides funding primarily for transport and energy infrastructure projects, as well as by the Connecting Europe Facility. [3]



Figure 1.1: Western Balkans – Eastern Mediterranean Corridor: Inland waterways and Roads, ports, rail-road terminals and airports [4]

More broadly, beyond promoting projects aimed at improving the infrastructure, the enlargement process also places strong emphasis on the implementation of technical standards and other soft measures, such as the simplification of border-crossing procedures, railway reforms, the development of information systems, road safety and maintenance schemes, as well as railway unbundling and third-party access.

Another important example of the integration of EU rules with the Western Balkans in the field of transport is the Transport Community. The Transport Community is an international organisation bringing together the European Union and the six Western Balkans partners (Albania, Bosnia and Herzegovina, Kosovo¹, North Macedonia, Montenegro and Serbia). Its main objective is to extend EU transport market rules, principles and policies to the Western Balkans through a legally binding framework. The Transport Community covers road, rail, inland waterway and maritime transport and aims to improve the development of transport networks between the EU and the Western Balkans. In particular, it supports the gradual extension of the TEN-T comprehensive and core networks to the region by identifying priority projects of regional interest [5].

Finally, macro-regional strategies also represent a key policy instrument within the European Union enlargement policies. These are integrated frameworks that bring together countries within a defined geographical area and commit them to close cooperation in order to enhance economic, social and territorial cohesion. In Europe, four macro-regional strategies have been established:

1. EU Strategy for the Baltic Sea Region (EUSBSR);
2. EU Strategy for the Danube Region (EUSDR);
3. EU Strategy for the Adriatic and Ionian Region (EUSAIR);
4. EU Strategy for the Alpine Region (EUSALP).

¹Reference to *Kosovo* or *XK* in this thesis is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence. This clarification applies throughout the entire document.

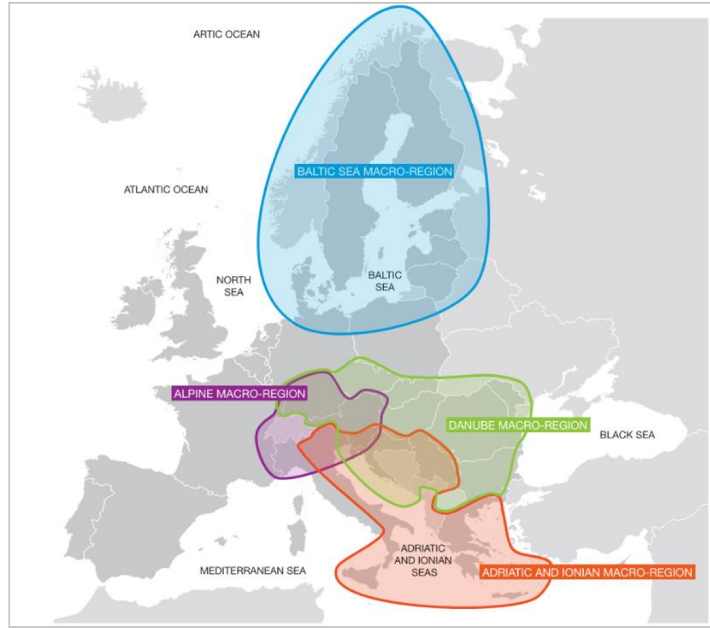


Figure 1.2: EU Macro-Regional Strategies [6]

Developed between 2009 (EUSBSR) and 2015 (EUSALP), these strategies aim to address shared challenges such as limited connectivity and climate change, as well as social issues like unemployment. Their ultimate goal is to promote strong cooperation among participating countries, while also supporting European policy objectives – such as the European Green Deal – and to bring citizens closer both to each other and to the European integration process [7].

This thesis focuses on the EU Strategy for the Adriatic and Ionian Region (EUSAIR) and involves the first update of the EUSAIR Multimodal Transport Model (EMTM) to the new base year 2023, replacing the previous version based on 2017.

1.1. EU Strategy for the Adriatic and Ionian Region (EUSAIR)

The EU Strategy for the Adriatic and Ionian Region (EUSAIR) is a macroregional strategy launched by the European Commission and endorsed by the European Council in 2014. It was developed jointly by the European Commission, the countries of the defined region and other relevant stakeholders, with the shared objective of improving cooperation on those issues of common interest than can both benefit individual countries and build a more prosperous, inclusive and sustainable Adriatic-Ionian region [8].

The EUSAIR brings together ten participating countries, involving a total population of over 70 million inhabitants: four EU Member States (Croatia, Greece, Italy and Slovenia), five EU candidate countries (Albania, Bosnia and Herzegovina, Montenegro, North Macedonia and Serbia) and one non-EU country (San Marino).

In Italy, only fourteen regions are part of the strategy: Abruzzo, Basilicata, Calabria, Emilia-Romagna, Friuli-Venezia Giulia, Lombardy, Marche, Molise, the Autonomous Provinces of Bolzano and Trento, Apulia, Sicily, Umbria and Veneto.

The strategy serves as a valuable instrument for candidate countries, complementing the EU's negotiating framework and other instruments used by the European Commission to support their progress towards accession.

1.1.1. EUSAIR Action Plan

The Strategy is implemented through an Action Plan, which defines the key priorities for the Adriatic-Ionian Region. With the Strategy's introduction in 2014, the first Action Plan was approved. Then, a revision process began in January 2022 to face new challenges and priorities. The revised Action Plan was officially adopted by the European Commission in May 2025, marking a renewed phase of regional cooperation across the Adriatic-Ionian Region. Through this updated framework, participating countries have also reaffirmed their commitment to supporting the EU accession process, so as to unlock the full potential of the region.

The countries of the Adriatic-Ionian Region operate within five thematic areas, known as Pillars:

1. Blue Sustainable Economy
2. Connecting the Region
3. Environmental Quality
4. Sustainable Tourism
5. Improved Social Cohesion.



Figure 1.3: EU Strategy for the Adriatic and Ionian Region (EUSAIR) and its five Pillars [9]

Pillar 2: Connecting the Region

Pillar 2 – Connecting the Region of the EUSAIR focuses on two main sectors: transport and energy. It is coordinated by Italy, Serbia and North Macedonia and aims to improve connectivity and interconnections within the Adriatic-Ionian area, as well as with the rest of Europe. The main objective is to develop a sustainable and efficient multimodal transport system and a well-integrated energy market.

In the EUSAIR Action Plan, this Pillar is structured around five priority topics:

1. Maritime transport
2. Multi-modal connectivity
3. Urban nodes
4. Energy networks
5. Decarbonising the energy systems.

1.1.2. Governance

To ensure the effective implementation of the Strategy and to establish the right priorities for the Region, three distinct yet interconnected levels of governance have been defined. In addition to the political level, which includes the Ministers for EU Funds and Ministers

of Foreign Affairs of the ten participating countries, the EUSAIR governance structure also comprises a coordinating level and an operational level.

The coordinating level includes:

- Governing Board: the strategic decision-making body responsible for the implementation of the Action Plan
- National Coordinators: representatives of national strategic positions
- Pillar Coordinators: they oversee the work of the respective Thematic Steering Groups (TSGs). At least two Pillar Coordinators are designated for each TSG, one from an EU Member State and one from a candidate country or San Marino
- European Commission
- Presidency and TRIO

The operational level is represented by Thematic Steering Groups (TSGs). These are operational-level bodies responsible for coordinating and guiding the implementation of the Strategy within their respective pillars. For Pillar 2 – Connecting the Region, two groups are set up: one for Transport and one for Energy.

In addition to these, the EUSAIR Governance Point plays a supporting role for the Strategy's governance bodies, while the EUSAIR Youth Council is an independent body that ensures the institutional involvement of young people. Finally, the European Commission's Directorate-General for Regional and Urban Policy (DG REGIO) supports the implementation of the Strategy by facilitating and assisting the actions of the participating countries.

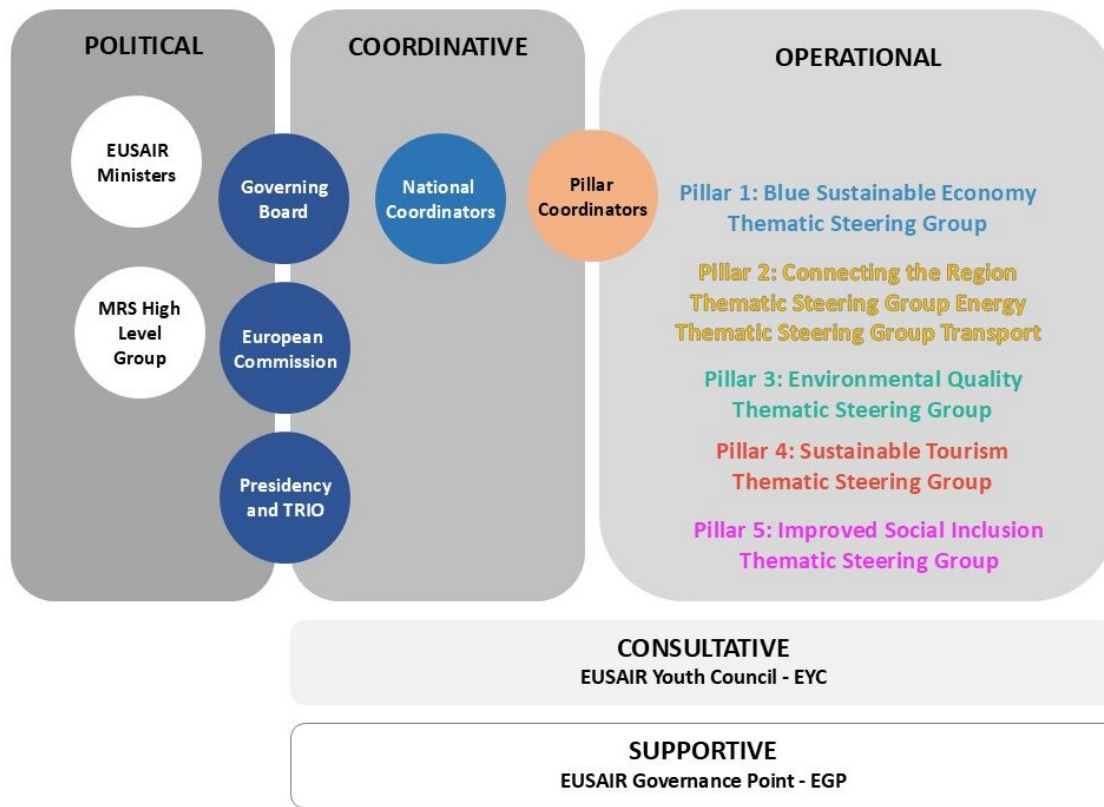


Figure 1.4: EUSAIR Governance and management architecture [10]

2 | Description of the Model

The model used to simulate transport flows within the EUSAIR study area (EMTM) was implemented using the *Cube* software. This chapter presents the main components of the model, with a focus on supply and demand, and the methodology guiding its development and implementation.

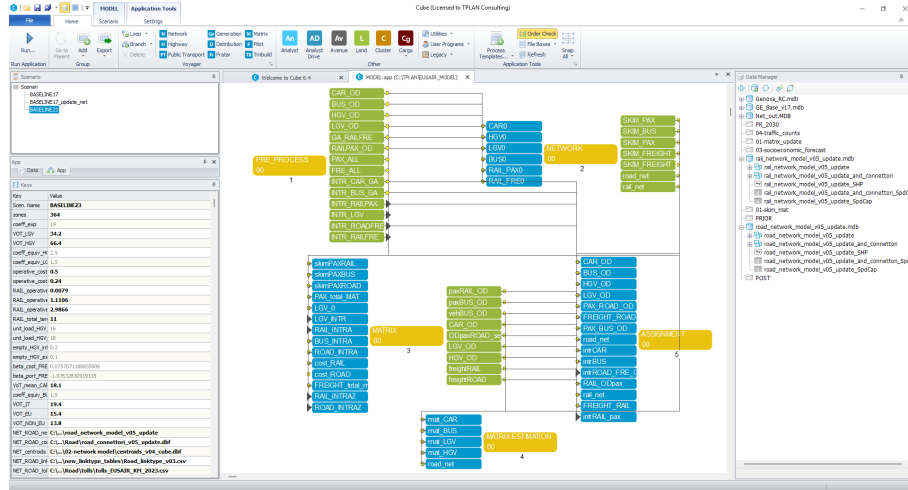


Figure 2.1: MODEL App in *Cube*

2.1. Supply Modelling

The supply-side model is based on the network provided by Tplan Consulting, originally developed for the 2017 Base Year model. The network covers almost all of Europe and Turkey and includes road, rail and maritime links.

The rail network was developed on the basis of the European network produced within the ETISplus project and TENtec and was subsequently updated using information encoded in OpenRailwayMap, as well as data derived from the network statements of national Infrastructure Managers. The road network was likewise developed starting from the European network produced within the ETISplus project and TENtec and subsequently updated using information available in documents published by European motorway concessionaires.

It was adopted a higher level of detail within the EUSAIR study area and a more aggregated representation for external zones. Within the EUSAIR area, the road and rail networks are nearly complete, particularly with respect to interzonal connections. Urban intrazonal links, public transport services and minor regional roads have been omitted. In contrast, zones external to the study area include only the main connections, primarily those forming the backbone of the European TEN-T corridors and those essential for identifying the principal access routes to the study area.

2.1.1. Rail and Road Network Updates

All networks were subsequently updated to 2023 by identifying the projects completed between 2017 and 2023, based on the project lists used in the previous model version and on new feedback provided by the countries involved in the EUSAIR initiative and other relevant stakeholders, and by updating the network parameters associated with the corresponding sections.

The projects included in the updated EUSAIR Masterplan Transport Model (EMTM) project lists comprise those contained in the European Transport Corridors (ETCs) Common Project List for the study area, as well as the projects already identified for the 2017 Base Year model. In addition, each country and relevant stakeholder involved in the initiative provides valuable feedback to validate the compiled list and to propose additions, modifications or removals based on the current status of investments. As a result, the road and rail networks represented in the EUSAIR model are more extensive than those included in the ETCs.

It should be noted that the road network projects included in the EUSAIR model also cover interventions involving an increase in the number of lanes, irrespective of whether they include the removal of at-grade intersections or the physical separation of carriageways. With regard to railway projects, initiatives exclusively related to the implementation of ERTMS technology are not included.

Completed Projects

The final project list compiled for the updated model includes projects completed by 2023, which are then used to update the network status and to assess if and how their effective implementation has influenced network performance. Accordingly, the first step in the network update process consisted of verifying which projects had been effectively completed, with particular focus on those finalised by 2022, so that their impacts could already be reflected in the 2023 network configuration. The tables below list the completed projects within the study area, distinguished between rail and road networks.

Table 2.1: Completed Rail Projects by Country by 2023

Country	Type	Project	Completion Year
Italy	New Construction	Bari-Bitetto 2nd track	2022
Slovenia	Upgrade	Zidani Most-Celje upgrade	2023
Slovenia	Upgrade	Poljcane-Slovenska Bistrica up- grade	2020
Croatia	New Construction	Zagreb Zapadni Kolovdor- Savski Marof reconstruction	2022
Serbia	New Construction	Belgrade-Stara Pazova high speed	2022
Greece	New Construction	Domokos-Lianokladi-Tithorea new line	2019

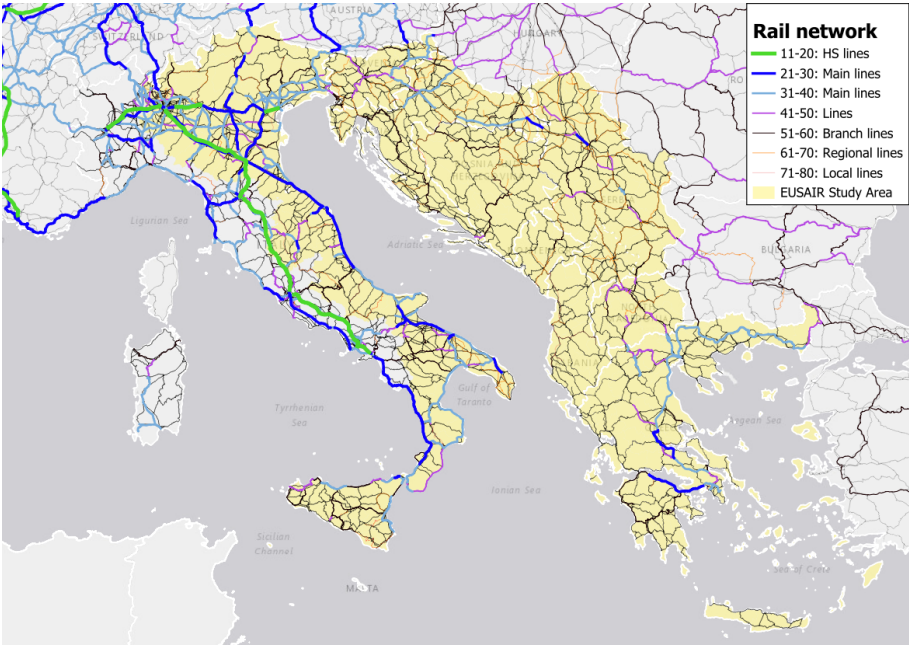


Figure 2.2: Rail network updated at 2023

Table 2.2: Completed Road Projects in Italy by 2023

Country	Type	Project	Completion Year
Italy	New Construction	A18 Ispica-Modica section	2022
Italy	Upgrade	A2 Motorway Salerno-Reggio Calabria upgrade	2021

Table 2.3: Completed Road Projects in Croatia by 2023

Country	Type	Project	Completion Year
Croatia	New Construction	Peljesac Bridge	2022

Table 2.4: Completed Road Projects in Greece by 2023

Country	Type	Project	Completion Year
Greece	New Construction	A3 Motorway: Trikkala-Xyniada section	2020
Greece	New Construction	A3 Motorway: Xyniada-Lamia section	2022
Greece	New Construction	Egnatia Odos: Moudania-Potidaia section	2021

Table 2.5: Completed Road Projects in Serbia by 2023

Country	Type	Project	Completion Year
Serbia	New Construction	Motorway Ljig-Obrenovac section	2020
Serbia	New Construction	Motorway Pirot-Nis section	2020
Serbia	New Construction	Motorway Leskovac-Vladicin Han section	2020

Table 2.6: Completed Road Projects in Montenegro by 2023

Country	Type	Project	Completion Year
Montenegro	New Construction	Bar-Boljare Highway: Smokovac - Matesevo section	2022
Montenegro	New Construction	Reconstruction of road: Niksic-Vilusi Expressway	2022

Table 2.7: Completed Road Projects in Bosnia and Herzegovina by 2023

Country	Type	Project	Completion Year
Bosnia and Herzegovina	New Construction	Motorway Banja Luka-Bukovac section	2019
Bosnia and Herzegovina	New Construction	Motorway Banja Luka-Doboj section	2019
Bosnia and Herzegovina	New Construction	Corridor Vc Motorway Johovac-Rudanka Interchange	2022
Bosnia and Herzegovina	New Construction	Svilaj Bridge in Svilaj-Odzak section	2021
Bosnia and Herzegovina	New Construction	Corridor Vc Tunnel Zenica-Donja Gracanica section	2021
Bosnia and Herzegovina	New Construction	Corridor Vc Motorway Klopce-Drivusa section	2021
Bosnia and Herzegovina	New Construction	Corridor Vc Motorway Tarcin-Ivan section	2022

Table 2.8: Completed Road Projects in Albania by 2023

Country	Type	Project	Completion Year
Albania	New Construction	Shkodra bypass	2021
Albania	New Construction	Road Kardhiq-Dervhina section	2022
Albania	New Construction	Tirana-Elbasan Motorway	2019
Albania	New Construction	Fier bypass	2020
Albania	New Construction	Levan-Vlore Motorway	2017
Albania	New Construction	Vlore bypass	2021
Albania	Upgrade	Fier-Tepelene rehabilitation and upgrade	2017

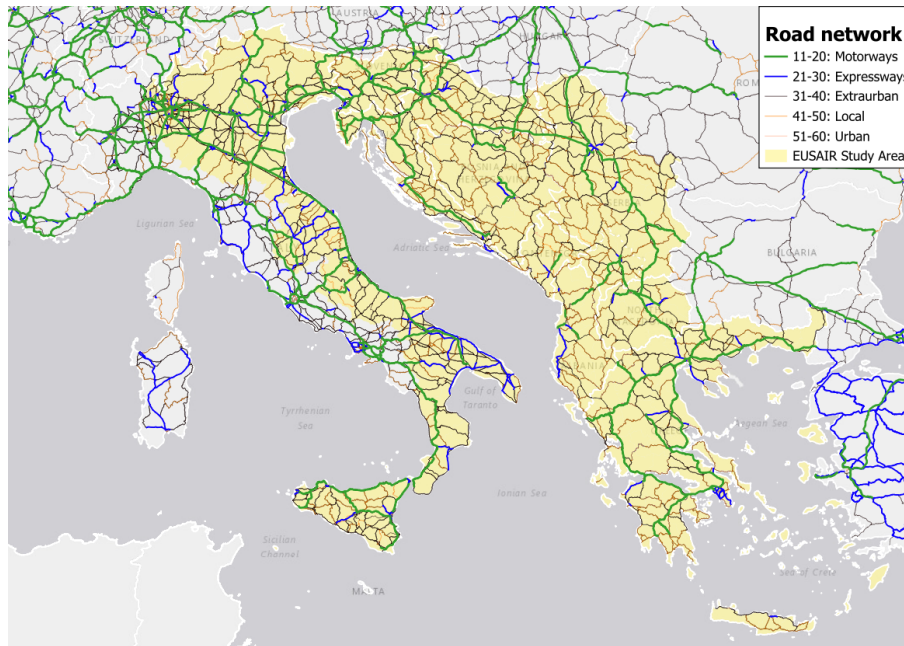


Figure 2.3: Road network updated at 2023

2.1.2. Rail and Road Network Parameters

To obtain a comprehensive overview of the network status in 2023, a set of key parameters describing the rail and road networks was reviewed and updated.

Rail Parameters

For the rail network, the updating of network sections was carried out using data from the network statements of the national Infrastructure Managers. In particular,

1. Croatia: data retrieved from HŽ Infrastruktura [11]
2. Greece: data retrieved from the Hellenic Railways Organisation [12]
3. Italy: data retrieved from the "e-PIR - Railway Network Information" of RFI [13]
4. North Macedonia: data retrieved from PE ŽRSM Infrastructure [14]
5. Serbia: data retrieved from Infrastructure of Serbian Railways JSC [15]
6. Slovenia: data retrieved from SŽ-Infrastruktura [16].

The following tables present country-level data for the selected railway network parameters, namely track gauge, traction type, voltage, number of tracks, maximum train length, maximum axle load and maximum operating speed for passenger and freight services. For illustrative purposes, maps depicting the maximum operating speed for passenger services and the maximum axle load are also provided.

Table 2.9: Track gauge by country

Track Gauge	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
1435 mm	96%	100%	100%	78%	100%	97%	100%	100%	100%	100%	100%
others	4%	0%	0%	22%	0%	3%	0%	0%	0%	0%	0%
Total [km]	22,747	321	941	2,326	2,385	11,653	238	611	2,852	1,141	279

Table 2.10: Traction type by country

Traction	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
Electrified	54%	0%	71%	29%	36%	67%	91%	37%	43%	49%	0%
Non-electrified	46%	100%	29%	71%	64%	33%	9%	63%	57%	51%	100%
Total [km]	22,759	321	941	2,349	2,385	11,642	238	611	2,852	1,141	279

Table 2.11: Voltage by country

Voltage	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
25 000 Volts, 50Hz AC	18%	0%	71%	27%	36%	3%	91%	37%	43%	0%	0%
3 000 Volts, DC	35%	0%	0%	0%	0%	64%	0%	0%	0%	49%	0%
15 000 Volts, 16 2/3 Hz AC	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%
Non-electrified	46%	100%	29%	71%	64%	33%	9%	63%	57%	51%	100%
Other	0%	0%	0%	2%	0%	0%	0%	0%	0%	0%	0%
Total [km]	22,767	321	941	2,354	2,385	11,645	238	611	2,852	1,141	279

Table 2.12: Number of tracks by country

Tracks	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
1	73%	100%	89%	71%	89%	62%	100%	100%	89%	73%	100%
2	27%	0%	11%	29%	11%	38%	0%	0%	11%	27%	0%
Total [km]	22,726	321	941	2,349	2,385	11,609	238	611	2,852	1,141	279

Table 2.13: Maximum train length by country

Max. Train Length	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
$L \geq 740$ m	1%	NA	0%	0%	0%	1%	0%	0%	2%	9%	0%
$500 \leq L < 740$ m	55%	NA	19%	100%	39%	46%	100%	100%	72%	50%	70%
$L < 500$ m	44%	NA	81%	0%	61%	54%	0%	0%	26%	40%	30%
Total [km]	20,104	–	917	1,623	1,404	11,060	226	611	2,843	1,141	279

Table 2.14: Maximum axle load by country

Max. Axle Load	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
$m \geq 22.5$ t	49%	0%	87%	23%	57%	48%	100%	59%	58%	52%	58%
$18 \text{ t} \leq m < 22.5$ t	43%	100%	13%	55%	39%	48%	0%	41%	23%	48%	42%
$m < 18$ t	8%	0%	0%	21%	4%	5%	0%	0%	19%	0%	0%
Total [km]	22,278	321	870	2,349	2,385	11,232	238	611	2,852	1,141	279

Table 2.15: Maximum operating speed for passenger trains by country

Max. Operating Speed (PAX)	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
$v \geq 200$ km/h	2%	NA	0%	0%	0%	5%	0%	0%	0%	0%	0%
$120 \leq v < 200$ km/h	34%	NA	0%	63%	10%	48%	0%	0%	2%	26%	0%
$v < 120$ km/h	64%	NA	100%	37%	90%	48%	100%	100%	98%	74%	100%
Total [km]	21,851	–	870	2,325	2,385	11,167	238	594	2,852	1,141	279

Table 2.16: Maximum operating speed for freight trains by country

Max. Operating Speed (FREIGHT)	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK
$v \geq 100$ km/h	37%	NA	0%	13%	26%	60%	0%	37%	1%	15%	NA
$80 \leq v < 100$ km/h	21%	NA	0%	68%	37%	17%	0%	31%	0%	31%	NA
$v < 80$ km/h	42%	NA	100%	20%	38%	23%	100%	32%	99%	55%	NA
Total [km]	18,980	–	870	1,900	1,357	10,028	238	594	2,852	1,141	–



Figure 2.4: Maximum axle load for rail network in the EUSAIR area



Figure 2.5: Maximum operating speed for passenger trains in the EUSAIR area

Road Parameters

In line with the approach adopted for the rail network, the main characteristics of the road network were reviewed by selecting two representative parameters: the number of

lanes per direction and the classification of tolled/non-tolled roads. The tables and maps are reported below, followed by a specific section on road toll rates, which were updated for the network from 2017 to 2023.

Table 2.17: Number of lanes per direction in the road network

Number of Lanes	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	SM	XK
1	77%	87%	94%	75%	79%	70%	93%	80%	84%	75%	59%	82%
2 or more	23%	13%	6%	25%	21%	30%	7%	20%	16%	25%	41%	18%
Total [km]	62,039	2,473	4,165	10,375	7,204	24,589	1,165	1,807	6,518	2,649	20	1,074

Table 2.18: Toll and non-toll roads by country

Toll Roads	TOT.	AL	BA	EL	HR	IT	ME	MK	RS	SI	SM	XK
Tolled	15%	3%	5%	22%	20%	13%	5%	18%	15%	24%	0%	15%
Not tolled	85%	97%	95%	78%	80%	87%	95%	82%	85%	76%	100%	85%
Total [km]	62,039	2,473	4,165	10,375	7,204	24,589	1,165	1,807	6,518	2,649	20	1,074



Figure 2.6: Number of lanes per direction in the road network



Figure 2.7: Toll and non-toll roads in the EUSAIR area

Road Toll Rates As part of the model update, road toll rates were also revised to reflect 2023 values, expressed in euros [€], if FIX, or euros per kilometre [€/km], if KM. For all countries included in the different model zones, toll rates are classified into five toll categories, in line with the classification scheme adopted by *Autostrade per l'Italia*, Italy's leading concessionarie for the construction and management of toll motorways [17]:

1. Class A: vehicles with two axles and a height less than or equal to 1.30 m (measured at the front axle)
2. Class B: vehicles with two axles and a height greater than 1.30 m (measured at the front axle)
3. Class 3: vehicles with three axles
4. Class 4: vehicles with four axles
5. Class 5: vehicles with five axles.

It should be noted that the last three classes are reported net of VAT.

Motorway toll rates are further distinguished between FIX and KM, depending on whether fixed or distance-based charges are applied.

For fixed toll rates, amounts were updated by applying a growth factor equal to 2.3% [18] to the tariffs referring to the year 2017 for all sections, with the exception of the

Rio–Antirrio Bridge in Greece [19] and the Sozina Tunnel in Montenegro [20], which were updated individually using the most recent toll values.

Table 2.19: Tolls for Rion–Antirion Bridge and Sozina Tunnel [€]

ID_TOLL	Toll Station	Class A	Class B	Class 3	Class 4	Class 5
304	Rion-Antirion Bridge	15.40	11.70	29.26	37.16	37.16
318	Tunnel Sozina	2.50	3.95	7.90	14.22	14.22

With regard to distance-based toll rates, an almost fully disaggregated update was carried out for each country, particularly within the EUSAIR area. In most cases, toll rates were calculated as a weighted average of motorway charges based on section lengths.

For Italy, a growth rate of 6.79% relative to 2017 was applied to the sections managed by *Autostrade per l'Italia*, based on specific analyses mainly derived from sources published by the *Ministry of Infrastructure and Transport* [18] [21] [22]. For sections managed by other concessionaires, a growth factor of 2.3% was applied.

Table 2.20: Toll rates in Italy by motorway, operator and typology [€/km]

ID	Motorway	Operator	Typology	Class A	Class B	Class 3	Class 4	Class 5
101	A1	Autostrade	Pianura	0.08	0.08	0.10	0.15	0.18
102	A1	Autostrade	Montagna	0.09	0.09	0.12	0.18	0.21
103	A4	SATAP A4	Pianura	0.12	0.12	0.15	0.23	0.28
105	A4	BS-PD	Pianura	0.07	0.07	0.09	0.14	0.16
107	A4	CAV	Pianura	0.10	0.10	0.13	0.20	0.24
109	A4	Autovie Venete	Pianura	0.08	0.08	0.11	0.17	0.19
112	A5	ATIVA	Montagna	0.09	0.09	0.13	0.19	0.22
114	A5	SAV	Montagna	0.21	0.21	0.29	0.45	0.52
118	A6	ATS	Montagna	0.09	0.09	0.13	0.19	0.22
119	A7	Mi-Serravalle	Pianura	0.06	0.06	0.08	0.12	0.15
122	A10	AutoFiori	Montagna	0.13	0.15	0.25	0.32	0.37
123	A11	SALT A11	Pianura	0.13	0.13	0.18	0.29	0.33
125	A12	SALT A12	Pianura	0.10	0.10	0.15	0.22	0.25
126	A12	SALT A12	Montagna	0.14	0.15	0.20	0.32	0.37
127	A12	SAT	Pianura	0.14	0.14	0.20	0.31	0.36
130	A15	SALT A15	Montagna	0.13	0.13	0.19	0.29	0.33
131	A18	CAS A18	Pianura	0.04	0.04	0.08	0.10	0.12
132	A18	CAS A18	Montagna	0.05	0.06	0.11	0.14	0.15
134	A20	CAS A20	Montagna	0.06	0.06	0.08	0.12	0.14
135	A21	SATAP A21	Pianura	0.09	0.09	0.12	0.18	0.21
136	A21	SATAP A21	Montagna	0.09	0.10	0.14	0.21	0.24
137	A21	Auto Centropadane	Pianura	0.07	0.07	0.09	0.14	0.16
139	A22	AutoBrennero	Pianura	0.07	0.07	0.09	0.13	0.16
140	A22	AutoBrennero	Montagna	0.08	0.08	0.10	0.15	0.18
142	A24	Strada dei Parchi	Montagna	0.11	0.11	0.14	0.21	0.25
143	A33	Autostrada Asti–Cuneo	Pianura	0.12	0.16	0.25	0.33	0.39
145	A35	BreBeMi Spa	Pianura	0.16	0.19	0.24	0.38	0.45

For Albania, two distinct companies were defined to account for the two motorway concessionaires, namely *Albanian Highway Concession* and *G2 INFRA*, which are respectively responsible for the A1 motorway sections between Milot and Morinë and between Kashar and Thumanë [23] [24].

Table 2.21: Toll rates for A1 motorway in Albania [€/km]

ID	Motorway	Operator	Class A	Class B	Class 3	Class 4	Class 5
156	A1	Albania (AHC)	0.04	0.08	0.11	0.16	0.16
182	A1	Albania (G2 INFRA)	0.12	0.18	0.25	0.35	0.35

For Bosnia and Herzegovina, a distinction is made between motorways under the jurisdiction of the Federation of Bosnia and Herzegovina and those of Republika Srpska. The two respective operators are *JP Autoceste FBiH* [25] and *RS Motorways* [26].

Table 2.22: Toll rates in Bosnia and Herzegovina [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
159	BosniaHerzegovina FBiH	0.06	0.10	0.12	0.20	0.20
160	BosniaHerzegovina RS	0.05	0.09	0.13	0.21	0.21

For Croatia, reference was made to the report “*National Report on Motorways in the Republic of Croatia 2023*”, published on the ASECAP website [27].

Table 2.23: Toll rates in Croatia [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
162	Croatia	0.08	0.06	0.25	0.25	0.25

For Greece, an average of the toll rates applied by the various concessionaires operating the motorway network was calculated, resulting in a single representative toll rate. These concessionaires are grouped under *HELLASTRON*, the Hellenic Association of Toll Road Network, and include:

1. NEA ATTIKI ODOS [28]
2. Olympia Odos [29]
3. MOREAS [30]
4. Nea Odos [31]
5. Kentriki Odos [32]
6. Aegean Motorway [33]

7. Nea Egnatia Odos [34]

Table 2.24: Toll rates in Greece [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
167	Greece	0.06	0.09	0.12	0.17	0.17

For North Macedonia, motorway toll rates were derived from the toll tariffs published by the Public Enterprise for State Roads [35].

Table 2.25: Toll rates in North Macedonia [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
172	North Macedonia	0.05	0.06	0.10	0.14	0.14

For Serbia, reference was made to the price list published by the motorway operator *LLC PUTEVI SRBIJE* [36].

Table 2.26: Toll rates in Serbia [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
176	Serbia	0.05	0.06	0.11	0.22	0.22

For the Slovenian motorway network, passenger cars are subject to a vignette-based tolling system. In order to derive a representative toll rate expressed in [€/km], a set of calculations was carried out, taking into account that a total of 8.6 million vignettes were sold in 2023 and that revenues from tolls amounted to 509.2 million euros [37]. In addition, the prices of the electronic vignette in 2023 are reported below:

Table 2.27: E-vignette prices for two-track motor and caravan vehicles in Slovenia [38]

E-vignette type	Price [EUR]
Annual e-vignette	117.50
Monthly e-vignette	32.00
Weekly e-vignette	16.00

For Classes 3, 4 and 5, the DarsGo tolling system applies an infrastructure charge expressed in €/km, differentiated according to vehicle class. For the purpose of this analysis, a CO₂ Class 1 vehicle compliant with Euro EEV and Euro VI standards was assumed.

Canone infrastrutturale in EURO/km, IVA esclusa		2 assi Classe R2	3 assi Classe R3	4 o più assi Classe R4
CO ₂ classe 1	EURO 0–III	0,200061	0,22229	0,462363
	EURO IV	0,160049	0,177832	0,36989
	EURO V	0,140043	0,155603	0,323654
	EURO EEV, VI	0,120036	0,133374	0,277418
CO ₂ classe 2		0,114035	0,126705	0,263547
CO ₂ classe 3	EURO VI	0,102031	0,113368	0,235805
CO ₂ classe 4		0,084026	0,093362	0,194192
CO ₂ classe 5	a zero emissioni	0,030009	0,033344	0,069354

Figure 2.8: Tolls for HGVs on the Slovenian motorway network [39]

Table 2.28: Toll rates in Slovenia [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
178	Slovenia	0.05	0.07	0.13	0.28	0.28

For Montenegro, which opened its first motorway section between Smokovac and Mateševu in 2022 [40], the calculated toll rates are reported below:

Table 2.29: Toll rates in Montenegro [€/km]

ID	Operator	Class A	Class B	Class 3	Class 4	Class 5
211	Montenegro	0.09	0.12	0.20	0.33	0.33

Kosovo does not have toll roads.

With regard to the other countries included in the model zones, Table 2.30 reports the corresponding distance-based toll rates. It should be noted that:

1. For Poland, toll rates were calculated first and subsequently applied to other Eastern European countries, namely Bulgaria, Romania, the Czech Republic, Hungary and Slovakia. For expressways in the Czech Republic and Hungary, toll rates were halved.
2. For all other countries, toll rates were increased by 2.3%.

Table 2.30: Toll rates in selected European countries [€/km]

ID	Country / Operator	Class A	Class B	Class 3	Class 4	Class 5
147	Bulgaria	0.09	0.13	0.22	0.30	0.30
154	Romania	0.09	0.13	0.22	0.30	0.30
157	Austria	0.10	0.15	0.19	0.27	0.41
158	Belgium	0.00	0.00	0.08	0.13	0.14
163	Czech Republic (MW)	0.09	0.13	0.22	0.30	0.30
164	Czech Republic (EW)	0.04	0.06	0.11	0.15	0.15
165	France	0.10	0.15	0.22	0.30	0.30
166	Germany	0.00	0.00	0.14	0.14	0.16
168	Hungary (MW)	0.09	0.13	0.22	0.30	0.30
169	Hungary (EW)	0.04	0.06	0.11	0.15	0.15
171	Liechtenstein	0.10	0.15	0.40	0.81	1.21
174	Poland	0.09	0.13	0.22	0.30	0.30
175	Portugal	0.07	0.06	0.14	0.14	0.14
177	Slovakia	0.09	0.13	0.22	0.30	0.30
179	Spain	0.18	0.18	0.29	0.37	0.37
180	Switzerland	0.10	0.15	0.40	0.81	1.21
181	Turkey	0.03	0.05	0.12	0.19	0.19

2.2. Demand Modelling

2.2.1. Zoning

The model zoning consists of 364 zones, of which 226 belong to the EUSAIR area, with the addition of the San Marino zone compared to the model developed for 2017. For the EUSAIR study area, zoning was defined at a “provincial” level and broadly corresponds to the NUTS-3 level defined by Eurostat. The countries for which this correspondence does not apply are Bosnia and Herzegovina, Montenegro and Kosovo. For these countries, the zoning system was specifically developed for the model, as Eurostat does not define NUTS-3 regions for Bosnia and Herzegovina and Kosovo, while for Montenegro it defines a single NUTS-3 region. The zoning adopted in the model subdivides these countries into several zones comparable in size to a NUTS-3 region.

It should be noted that although 102 zones are defined for Italy, only 68 of them actually belong to the EUSAIR area.

Table 2.31: Zoning by country for the EMTM

Country	Code	Number of zones	EUSAIR
Albania	AL	12	1
Bosnia and Herzegovina	BA	18	1
Croatia	HR	21	1
Greece	EL	46	1
Italy	IT	102	1
Kosovo	XK	7	1
Montenegro	ME	8	1
North Macedonia	MK	8	1
San Marino	SM	1	1
Serbia	RS	25	1
Slovenia	SI	12	1
Austria	AT	19	0
Belgium	BE	1	0
Bulgaria	BG	13	0
Switzerland	CH	6	0
Cyprus	CY	1	0
Czech Republic	CZ	1	0
Germany	DE	4	0
Denmark	DK	1	0
Estonia	EE	1	0
Spain	ES	1	0
Finland	FI	1	0
France	FR	3	0
Hungary	HU	12	0
Ireland	IE	1	0
Liechtenstein	LI	1	0
Lithuania	LT	1	0
Luxembourg	LU	1	0
Latvia	LV	1	0
Malta	MT	1	0
Netherlands	NL	1	0
Norway	NO	1	0
Poland	PL	3	0

Country	Code	Number of zones	EUSAIR
Portugal	PT	1	0
Romania	RO	8	0
Sweden	SE	1	0
Slovakia	SK	1	0
Turkey	TR	15	0
United Kingdom	UK	1	0
External	XX	2	1
Total		364	

For each model zone, a macro-group (MC_GROUP) was also defined. In most cases, this corresponds to the country to which the zone belongs, with the exception of Italy, for which the macro-groups are defined as follows:

1. IT_NW: North-West Italy
2. IT_NE: North-East Italy
3. IT_CNT: Central Italy
4. IT_SUD: Southern Italy
5. IT_ISL: Italian Islands

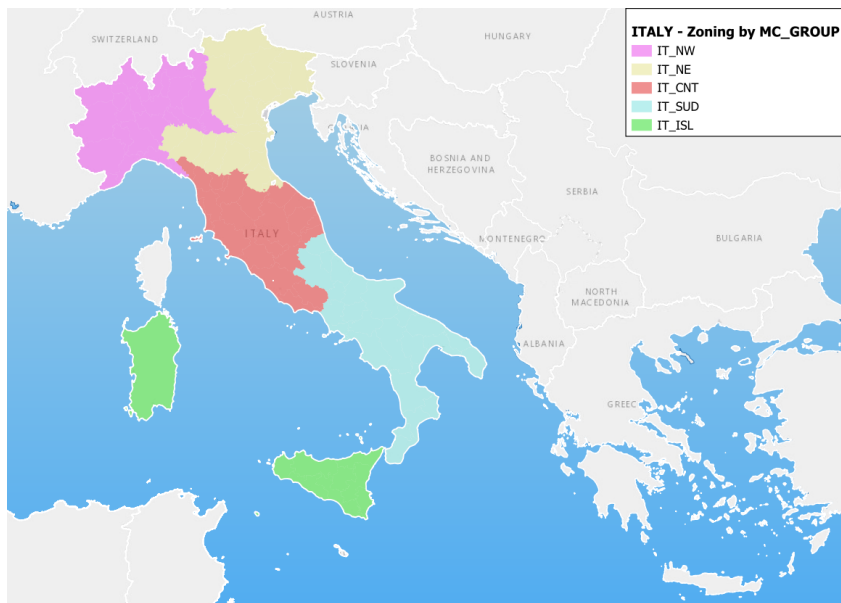


Figure 2.9: MC_GROUP in Italy

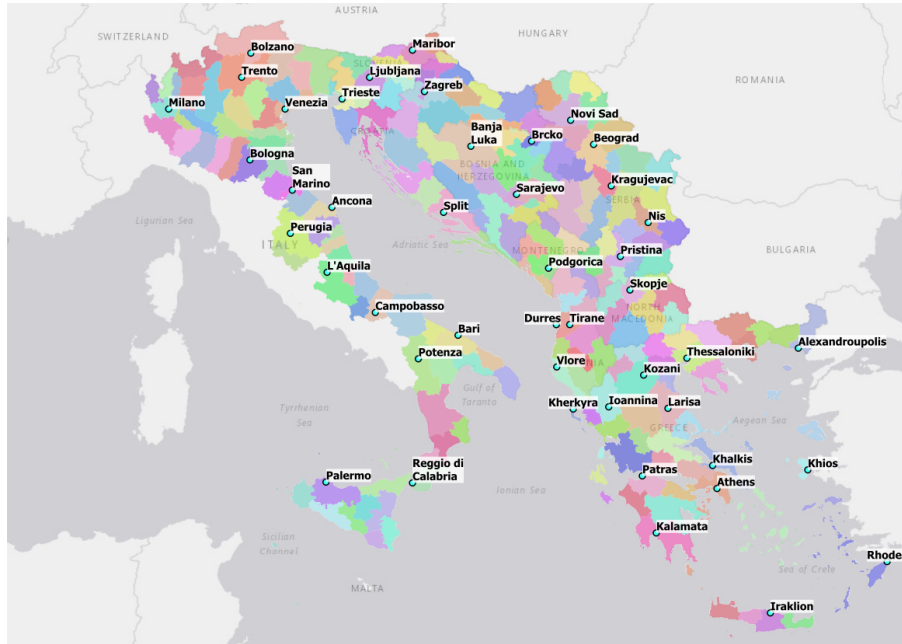


Figure 2.10: Zoning of the EUSAIR area and main cities at NUTS-2 level

2.2.2. Socioeconomic analysis of the study area

One of the first steps in this study to define the area of interest and better understand its context and transport needs is the analysis of key socio-economic conditions. This phase is particularly important because the Adriatic-Ionian Region is characterized by significant internal inequalities, not only within the region itself but also within the countries. In particular, the Western Balkans are characterized by large and dense capitals, which contrast strongly with almost abandoned rural and peripheral areas. While there are still clear distinctions between the country's North and South, the current situation in Italy is more uniform.

In general, the methodology used for data collection relies on Eurostat data for 2023 or on national statistical institutes when Eurostat data were not available. The statistical unit considered is NUTS 3, in accordance with the classification developed by the EU. When NUTS 3 level data were not available for 2023, the latest available data were adjusted by applying a growth/decline rate derived from NUTS 2 or NUTS 1 level statistics.

Population

Population data refer to the year 2023 and are mainly collected from the Eurostat dataset "Population on 1 January by age group, sex and NUTS 3 region" [41], with a few exceptions:

- Albania: data retrieved from National Institute of Statistics (*Instituti i Statistikave – INSTAT*) [42];
- Bosnia and Herzegovina: data retrieved from Federal Statistical Office (*Federalni zavod za statistiku – FZS*) [43], Republika Srpska Institute of Statistics (Републички завод за статистику Република Српска) - RZS [44] and Agency for Statistics of Bosnia and Herzegovina (*Agencije za statistiku Bosne i Hercegovine – BHAS*) [45]
- Kosovo: data retrieved from Kosovo Agency of Statistics (*Agjencia e Statistikave të Kosovës - ASK; Agencija za statistiku Kosova*) [46]
- Montenegro: data retrieved from Statistical Office of Montenegro (Uprava za statistiku Crne Gore – MONSTAT) [47]
- San Marino: data retrieved from the Office of Economic Planning, Data Processing and Statistics (*Ufficio Informatica, Tecnologia, Dati e Statistica - Dipartimento Funzione Pubblica*) [48].

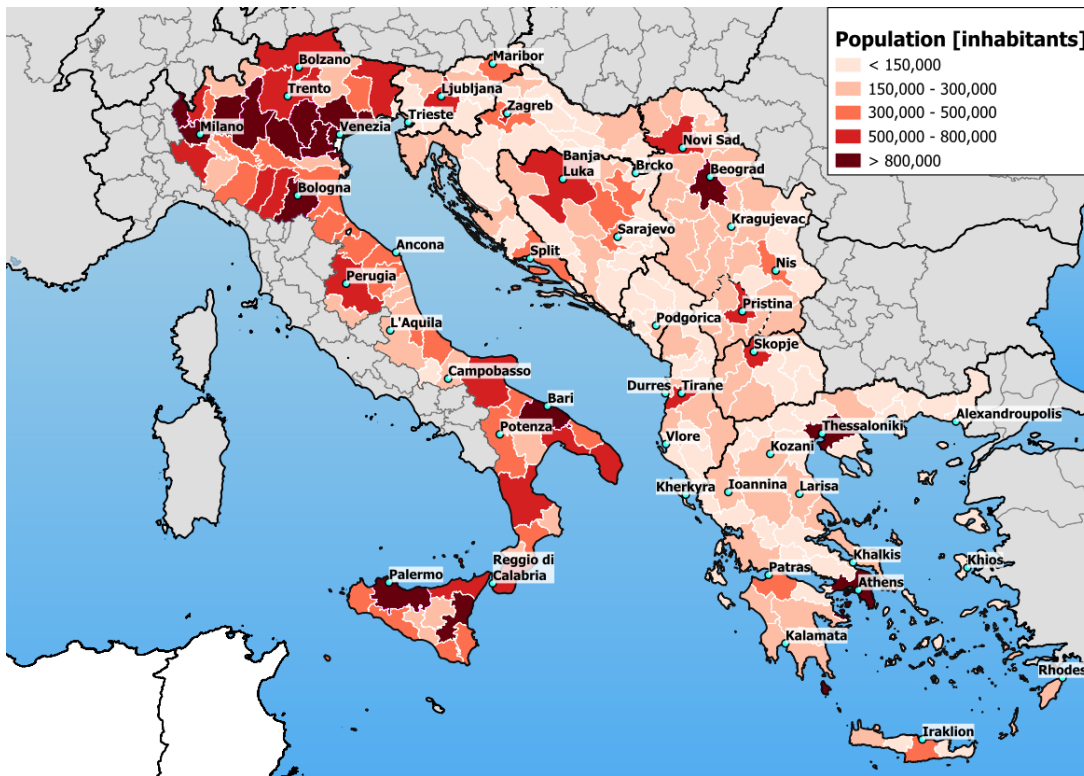


Figure 2.11: Population distribution in the EUSAIR area

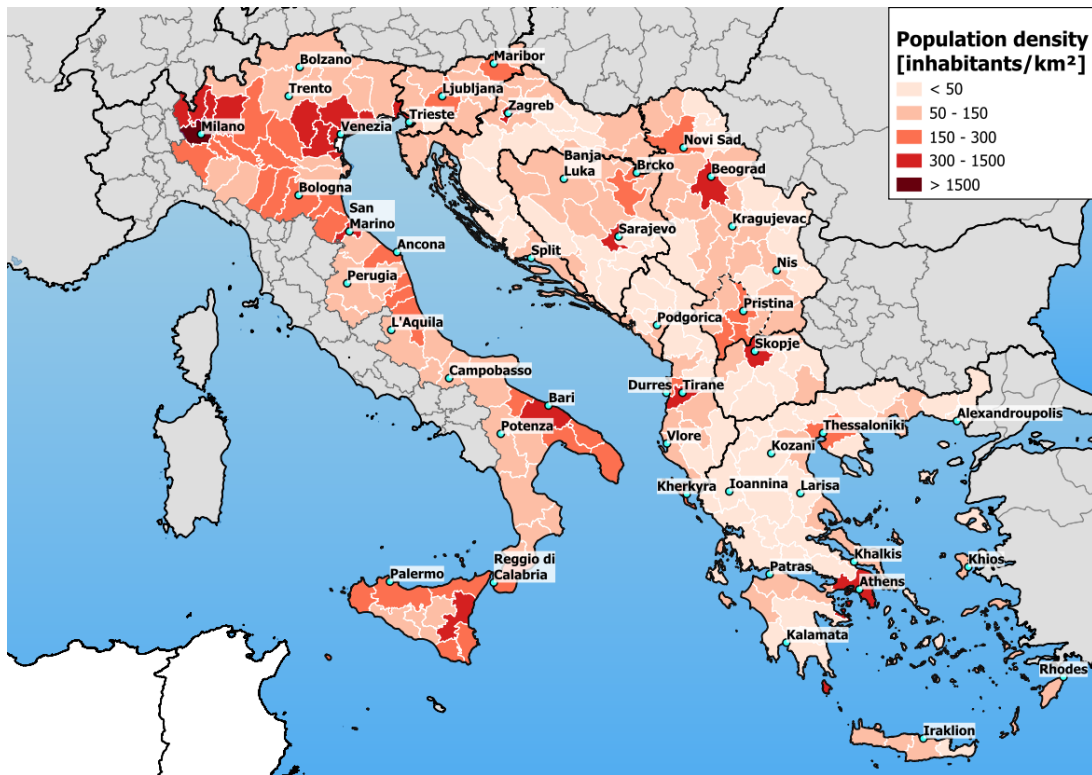


Figure 2.12: Population density in the EUSAIR area

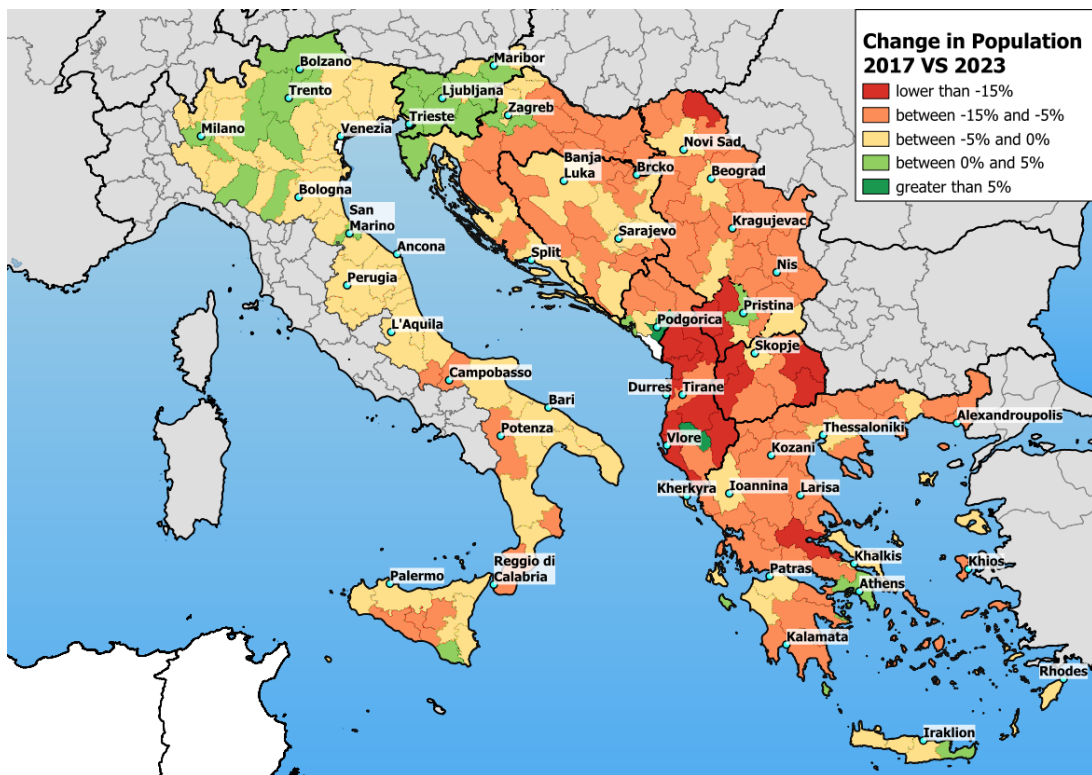


Figure 2.13: Population change in the EUSAIR area (2017–2023)

Gross Domestic Product (GDP)

The collection of GDP data was slightly more complex due to the lack of updated information for the 2023 Baseline Year at the NUTS-3 level, even for some EU Member States. Where necessary, the data required additional elaboration: in some cases, a growth (or decline) rate was applied based on the change observed between 2022 and 2023 at the NUTS-2 level (see Equation (2.1)); in other cases, the national GDP (NUTS-0 level) was proportionally distributed across NUTS-3 zones using population data as the distribution criterion (see Eq. (2.2)).

$$GDP_{NUTS3,2023} = \frac{GDP_{NUTS3,2022}}{GDP_{NUTS2,2022}} \times GDP_{NUTS2,2023} \quad (2.1)$$

$$GDP_{NUTS3,2023} = \frac{POP_{NUTS3,2023}}{POP_{NUTS0,2023}} \times GDP_{NUTS0,2023} \quad (2.2)$$

In particular, for the countries listed below, the Eurostat dataset “Gross domestic product (GDP) at current market prices by NUTS 3 region” [49] was used as the main source:

1. Croatia, North Macedonia, Slovenia: NUTS-3 data for 2023 available
2. Greece, Italy, Serbia: NUTS-3 data elaborated as described in Eq. (2.1)
3. Montenegro: NUTS-3 data elaborated as described in Eq. (2.2)

For the remaining countries, data were obtained from the respective national statistical institutes:

- Albania: data retrieved from National Institute of Statistics (*Instituti i Statistikave – INSTAT*) [50];
- Bosnia and Herzegovina: data retrieved from Federal Statistical Office (*Federalni zavod za statistiku – FZS*) [51], Republika Srpska Institute of Statistics (Републички завод за статистику Република Српска) - RZS) [52] and Agency for Statistics of Bosnia and Herzegovina (*Agencije za statistiku Bosne i Hercegovine – BHAS*) [53] and elaborated as described in Eq. (2.2)
- Kosovo: data retrieved from Central Bank of the Republic of Kosovo (*Banka Qendrore e Republikës së Kosovës - BQK; Centralna banka Republike Kosovo - CBK*) [54] and elaborated as described in Eq. (2.2)
- San Marino: data retrieved from the Office of Economic Planning, Data Processing and Statistics (*Ufficio Informatica, Tecnologia, Dati e Statistica - Dipartimento*

Funzione Pubblica) [55].

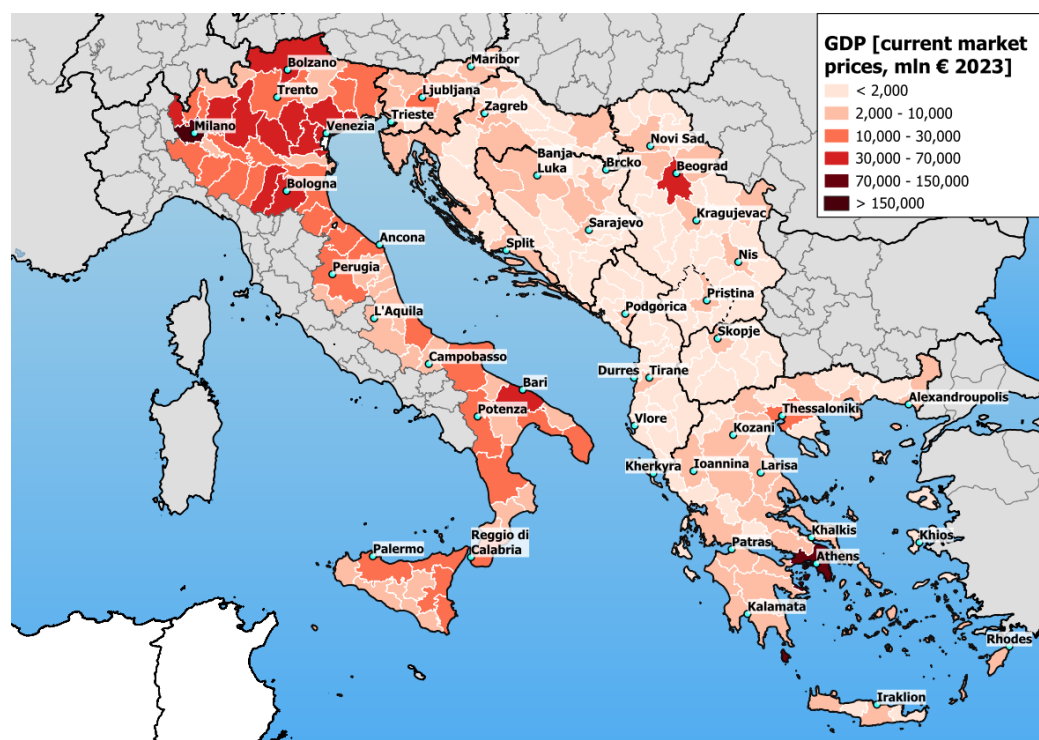


Figure 2.14: GDP distribution in the EUSAIR area

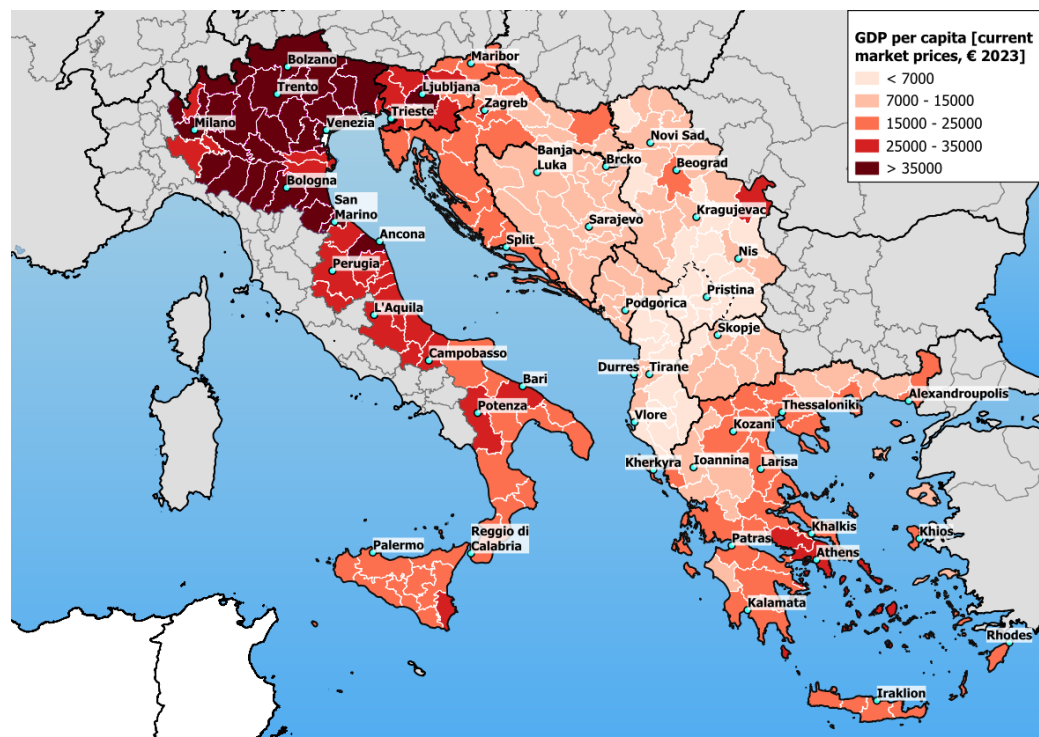


Figure 2.15: GDP per capita in the EUSAIR area

To compare GDP values between 2017 and 2023, the GDP of each country was deflated using the Harmonised Index of Consumer Prices (HICP) [56], in order to account for inflation. As HICP data for Bosnia and Herzegovina were not available in the Eurostat database, the index was approximated by taking the average of the Western Balkan countries. Subsequently, the compound annual growth rate (CAGR) was calculated according to the formula reported in the Eq. (2.3).

$$\text{CAGR}_{\text{harm}} = \left(\frac{\text{GDP}_{2023, \text{harm}}}{\text{GDP}_{2017, \text{harm}}} \right)^{\frac{1}{2023-2017}} - 1 \quad (2.3)$$

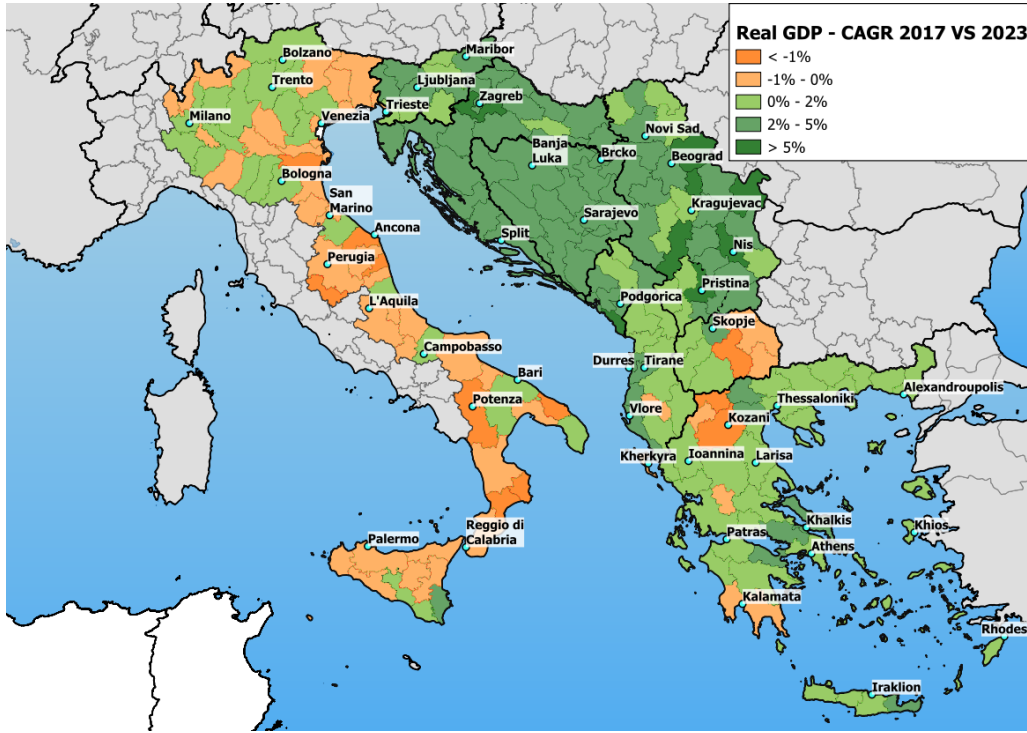


Figure 2.16: Real GDP - CAGR in the EUSAIR area (2017–2023)

Employees

The collection of employment data faced the same issues already discussed in Section 2.2.2, particularly with regard to the lack of updated data for 2023 at the NUTS-3 level. Accordingly, the following equations were used for data processing:

$$\text{EMPL}_{\text{NUTS3},2023} = \frac{\text{EMPL}_{\text{NUTS3},2022}}{\text{EMPL}_{\text{NUTS2},2022}} \times \text{EMPL}_{\text{NUTS2},2023} \quad (2.4)$$

$$EMPL_{NUTS3,2023} = \frac{POP_{NUTS3,2023}}{POP_{NUTS0,2023}} \times EMPL_{NUTS0,2023} \quad (2.5)$$

In particular, for the countries listed below, the Eurostat dataset “Employment (thousand persons) by NUTS 3 region” [57] was used as the main source:

1. Croatia and Slovenia: NUTS-3 data for 2023 available
2. Greece, Italy, North Macedonia and Serbia: NUTS-3 data elaborated as described in Eq. (2.4)

For the remaining countries, data were obtained from the respective national statistical institutes:

- Albania: data retrieved from National Institute of Statistics (*Instituti i Statistikave – INSTAT*) [58]
- Bosnia and Herzegovina: data retrieved from Federal Statistical Office (*Federalni zavod za statistiku – FZS*) [43], Republika Srpska Institute of Statistics (Републички завод за статистику Република Српска) - RZS) [44] and Agency for Statistics of Bosnia and Herzegovina (*Agencije za statistiku Bosne i Hercegovine – BHAS*) [53]
- Kosovo: data retrieved from Kosovo Agency of Statistics (*Agjencia e Statistikave të Kosovës - ASK; Agencija za statistiku Kosova*) [59] and elaborated as described in Eq. (2.5)
- San Marino: data retrieved from the Office of Economic Planning, Data Processing and Statistics (*Ufficio Informatica, Tecnologia, Dati e Statistica - Dipartimento Funzione Pubblica*) [48].

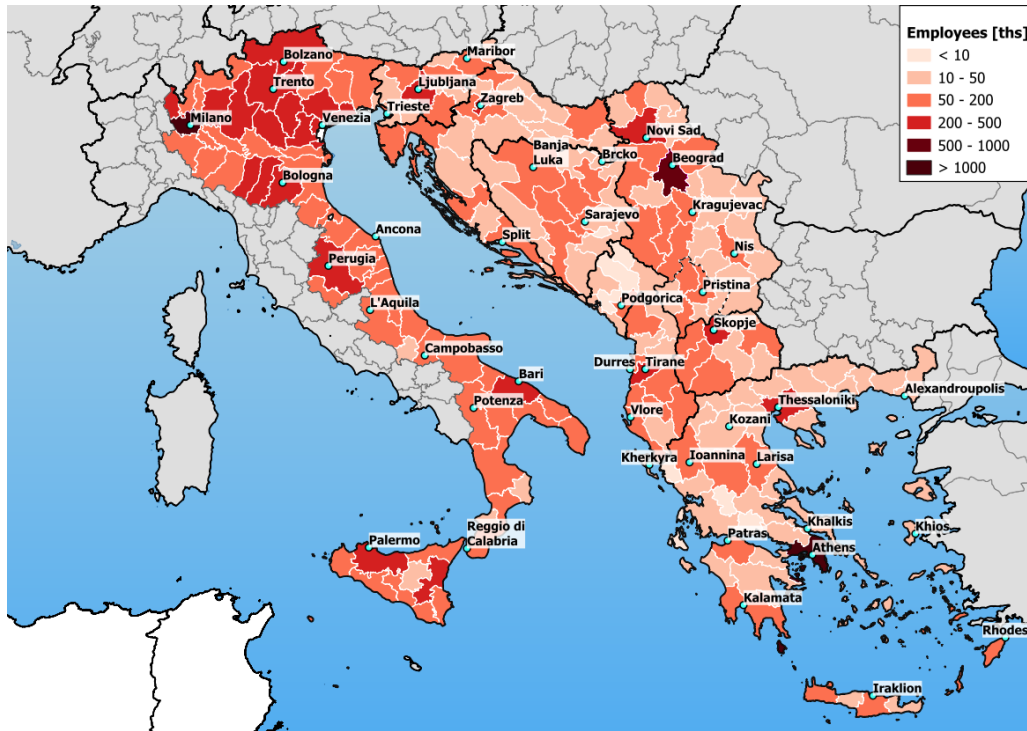


Figure 2.17: Employees distribution in the EUSAIR area

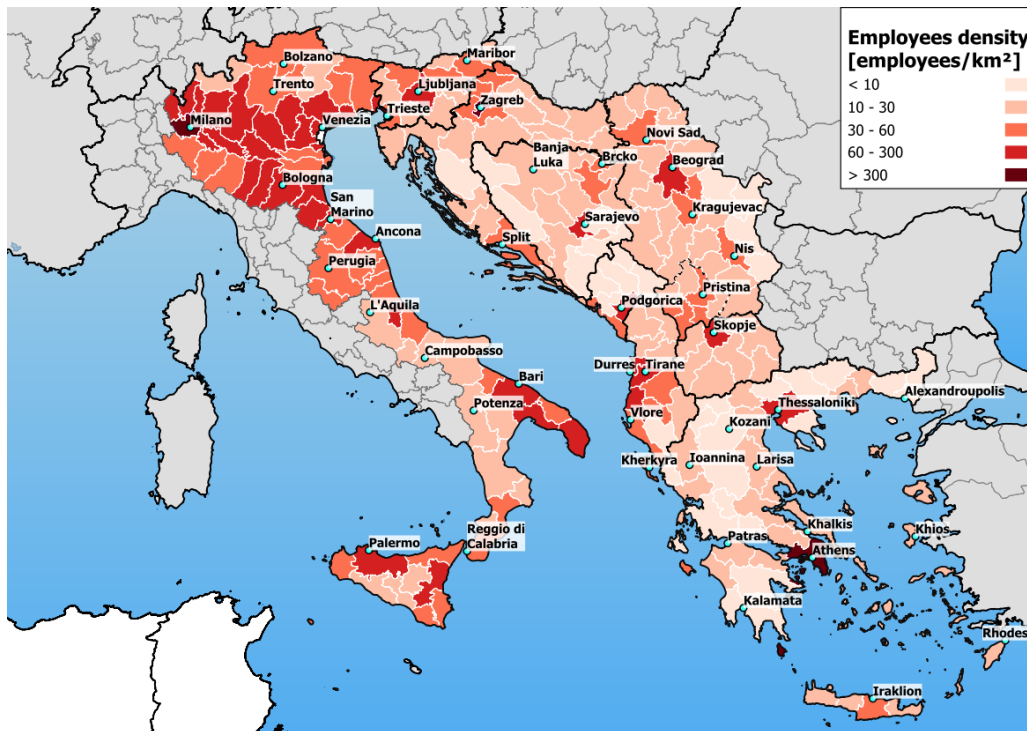


Figure 2.18: Employees density in the EUSAIR area

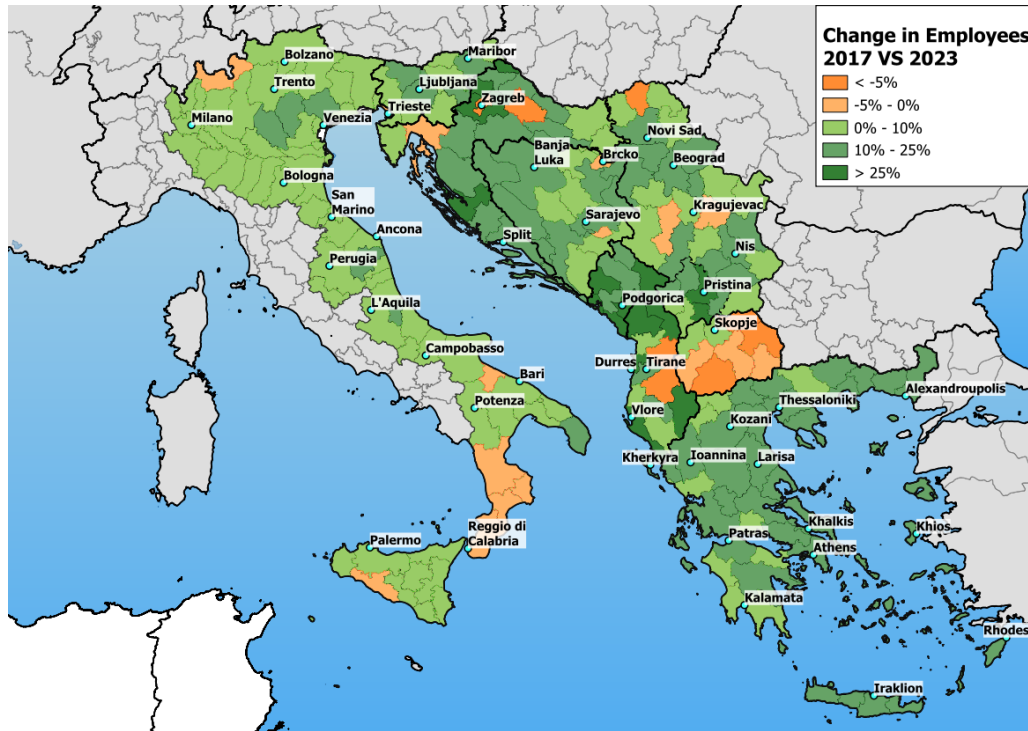


Figure 2.19: Employees change in the EUSAIR area (2017-2023)

Car Ownership

Another key indicator for understanding the current transport conditions in the region is car ownership. For data collection, the Eurostat database “Passenger cars per thousand inhabitants” [60] was used for all countries in the EUSAIR area, with the exception of San Marino, whose data were obtained from the “Statistical Bulletin” for the fourth quarter of 2023 [48].

Table 2.32: Car ownership [cars/1000 inhab.] by country in the EUSAIR area - 2017 vs 2023

Country	2017	2023	Change
Albania	145	292	+101%
Bosnia and Herzegovina	252	306	+21%
Croatia	398	495	+24%
Greece	487	565	+16%
Italy	643	694	+8%
Kosovo	152	208	+37%
Montenegro	310	389	+25%
North Macedonia	194	303	+56%
San Marino	1070	1032	-4%
Serbia	281	362	+29%
Slovenia	541	579	+7%

2.2.3. Origin-Destination Matrix

The initial demand matrices were developed based on the matrices produced within the ETISplus project [61], which were subsequently modified. The matrices are distinguished between passenger and freight demand and across the different transport modes. In addition, passenger matrices are further disaggregated by trip purpose, namely business, commuting, private and vacation.

For the update to the 2023 reference year, taking into account the addition of the San Marino zone, the matrices were renumbered and updated. The corresponding matrices for San Marino were developed using Floating Car Data (FCD) collected within the area.

All matrices are expressed in Generation–Attraction (GA) format, with the exception of the LGV matrix, which is already defined in Origin–Destination (OD) format, as it is assigned offline.

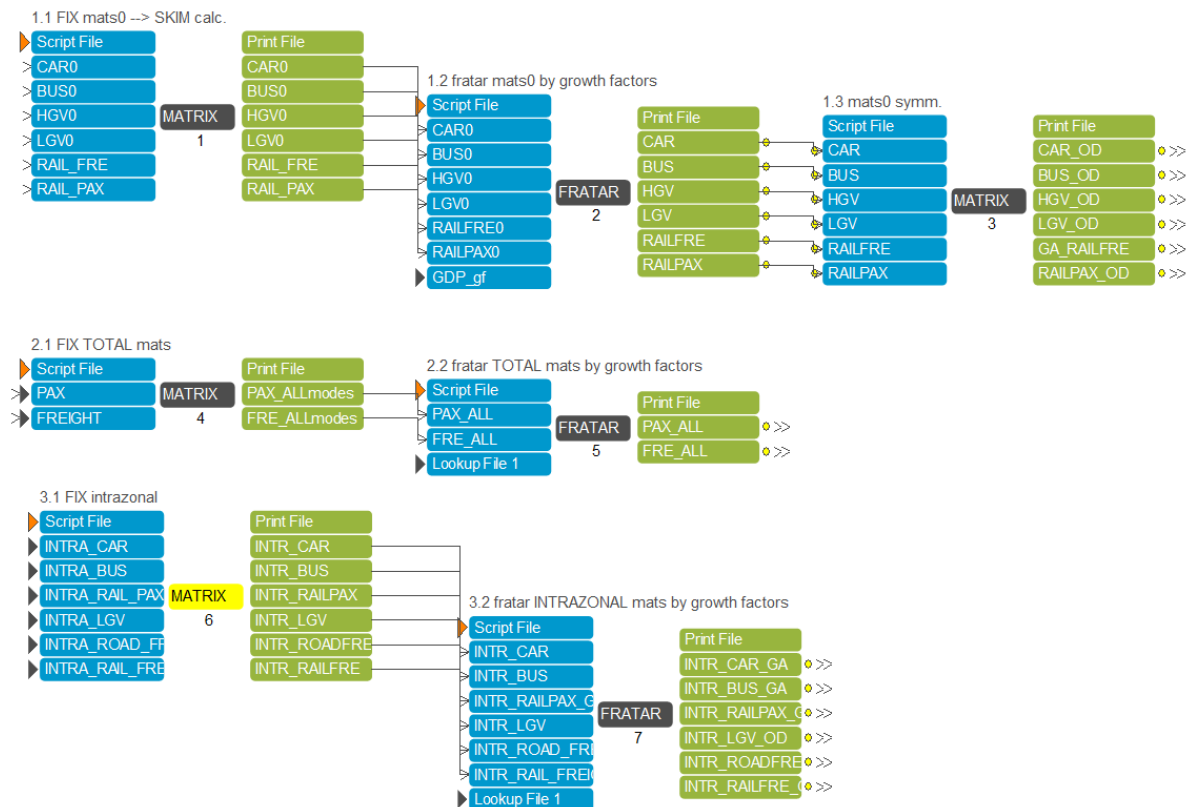


Figure 2.20: Pre-process of the matrices

Traffic Counts Data

One of the fundamental components of the model is matrix calibration, which is performed by comparing the results of an initial assignment with traffic count data collected for the various road sections of the network. These data typically refer to Average Annual Daily Traffic (AADT) and differ by country depending on the information available from online sources or on feedback received directly from national ministries or other stakeholders.

Albania Traffic count data were not available online, nor were any relevant feedback received at the time of writing and result processing for this thesis. Moreover, the extensive modifications to the network since 2017 did not allow the adaptation of previously available data to the new 2023 base year.

Bosnia and Herzegovina Traffic count data for 2023 for the Federation of Bosnia and Herzegovina are available online on the website of Roads of the Federation of Bosnia and Herzegovina [62], while traffic counts for the motorway section between Sarajevo Sjever and Zenica Jug were derived from a document published by JP Autoceste FBiH [63].

With regard to Republika Srpska, the most recent traffic count data available online refer to 2019 [64]; therefore, these data were updated to 2023 by applying growth factors based on observed traffic volumes in the area.

Croatia Traffic count data for Croatia for 2023 are available on the website of *Hrvatske Ceste* [65].

Greece Traffic count data for 2023 for selected Greek motorway sections were provided by the Hellenic Ministry of Infrastructure and Transport.

Italy Traffic count data for Italy for 2023 were derived from multiple sources:

1. For roads under the responsibility of ANAS, reference was made to the official ANAS website [66].
2. For the majority of motorway sections, data from AISCAT were used [67]. The most recent data available refer to 2022; therefore, growth rates were applied to update them to 2023, namely 3% for cars and 1% for HGVs and LGVs, based on a report published by the Ministry of Infrastructure and Transport (MIT) on mobility trends for the fourth quarter of 2024 [68].
3. Traffic counts for selected sections in the Emilia-Romagna region were obtained from the regional traffic portal, which provides publicly available traffic flow data online [69].

Montenegro Traffic count data were derived from a document provided by the Ministry of Transport of Montenegro (“Medium-Term Program for the Construction, Reconstruction, Maintenance and Protection of State Roads in Montenegro until 2028”), with the exception of the motorway section between Smokovac and Mateševo, for which AADT values are available online [70].

North Macedonia Traffic count data referring to 2017 were updated to 2023 by applying growth rates based on traffic volumes reported in the European Commission’s Statistical Pocketbook 2025 [71]. At the time of writing and result processing for this thesis, no additional feedback had been provided.

San Marino Traffic counts for the sections between Italy and San Marino were derived from the corresponding Italian road sections.

Serbia Traffic count data for 2023 are available on the website of LLC *PUTEVI SRBIJE* [72].

Slovenia Traffic count data for 2023 were provided by the Ministry of Infrastructure.

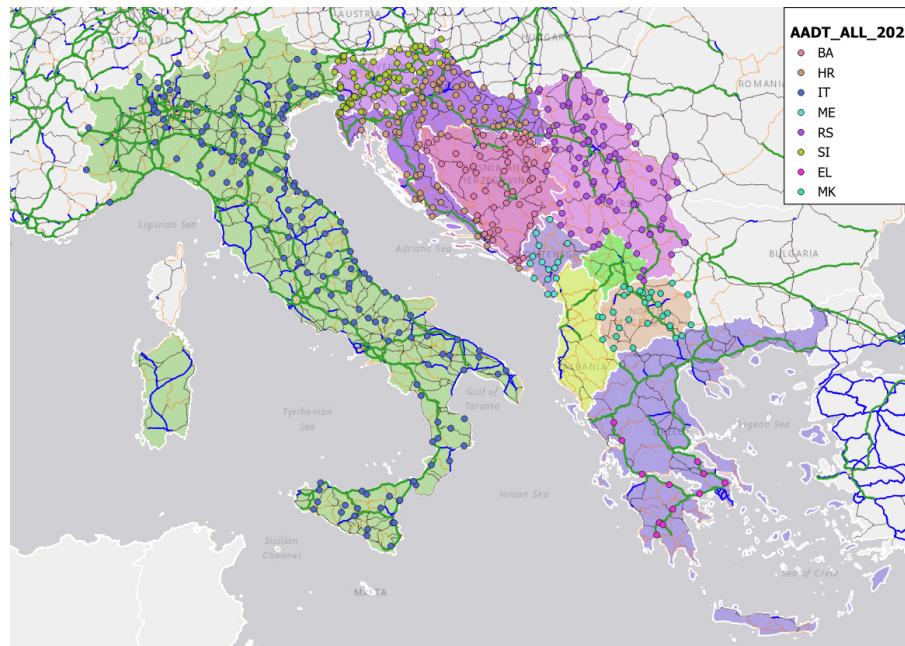


Figure 2.21: AADT in the EUSAIR area

Socioeconomic Forecasts

In view of the scenarios that will be developed for the future scenarios of 2035, 2040 and 2050, as well as for the update to the 2023 reference year, projections of selected key socio-economic drivers were developed for the model.

Population Up to 2024, data are observed values and are derived from Eurostat or from national statistical institutes, as already described in Section 2.2.2. Only in the case of Bosnia and Herzegovina is the World Economic Outlook of the International Monetary Fund (IMF) [73] used as the sole data source. For data from 2025 onwards, different sources and approaches are adopted depending on the countries considered. For European Union countries, data from 2025 onwards are taken from the Eurostat dataset “Population on 1st January by age, sex and type of projection” [74] and are calculated on a year-by-year basis; for the other countries, reference is again made to the World Economic Outlook, and an average growth rate between 2023 and 2030 is computed. For illustrative purposes, the first part of the table reporting data up to 2030 is shown.

Table 2.33: Annual population percentage change by country

Year	AL	BA	EL	HR	IT	ME	MK	RS	SI	XK	SM
2017 → 2023	-3.00%	-0.73%	-0.54%	-0.64%	-0.27%	+0.04%	-2.11%	-0.97%	+0.46%	-1.90%	+0.35%
2024	-1.16%	-0.26%	-0.77%	-1.33%	-0.03%	-0.06%	-0.20%	-0.57%	-0.15%	-1.09%	+0.71%
2025	-1.00%	-0.30%	-0.52%	-0.59%	-0.09%	+0.05%	-0.56%	-0.73%	+0.01%	-0.22%	+0.48%
2026	-1.00%	-0.30%	-0.56%	-0.59%	-0.09%	+0.05%	-0.56%	-0.73%	+0.01%	-0.22%	+0.48%
2027	-1.00%	-0.30%	-0.59%	-0.57%	-0.07%	+0.05%	-0.56%	-0.73%	-0.00%	-0.22%	+0.48%
2028	-1.00%	-0.30%	-0.58%	-0.85%	-0.05%	+0.05%	-0.56%	-0.73%	-0.03%	-0.22%	+0.48%
2029	-1.00%	-0.30%	-0.57%	-0.56%	-0.05%	+0.05%	-0.56%	-0.73%	-0.03%	-0.22%	+0.48%
2030	-1.00%	-0.30%	-0.57%	-0.55%	-0.04%	+0.05%	-0.56%	-0.73%	-0.04%	-0.22%	+0.48%

GDP Up to 2024, data are observed values and are derived from different sources depending on whether countries belong to the European Union or not. For Croatia, Greece, Italy and Slovenia, data up to 2027 are taken from the European Economic Forecasts published annually by the European Commission in autumn. In particular, the Autumn 2025 edition was used [75], together with the editions for the years 2021, 2022, 2023 and 2024 [76] [77] [78] [79]. From 2031 onwards, data are based on the European Commission's 2024 Ageing Report [80]. For the intermediate years between 2027 and 2031, a linear interpolation was applied between the 2027 and 2031 values.

$$\text{GDP_growth_rate}_i = \text{GDP_growth_rate}_{i-1} + \frac{\text{GDP_growth_rate}_{2031} - \text{GDP_growth_rate}_{2027}}{2031 - 2027}$$

$$i = 2028, 2029, 2030$$

(2.6)

Table 2.34: Annual GDP growth rates for EU countries

Year	EL	HR	IT	SI
2018	1.7%	2.9%	0.9%	4.4%
2019	1.9%	3.4%	0.5%	3.5%
2020	-9.3%	-8.6%	-9.0%	-4.2%
2021	8.7%	12.6%	8.9%	8.4%
2022	5.5%	7.3%	4.8%	2.7%
2023	2.1%	3.8%	1.0%	2.4%
2024	2.1%	3.8%	0.7%	1.7%
2025	2.1%	3.2%	0.4%	1.0%
2026	2.2%	2.9%	0.8%	2.4%
2027	1.7%	2.5%	0.8%	2.6%
2028	1.6%	2.3%	1.0%	2.3%
2029	1.4%	2.1%	1.1%	2.1%
2030	1.3%	1.9%	1.3%	1.8%
2040	1.1%	1.7%	1.4%	1.5%
2050	1.1%	1.4%	1.4%	1.0%

For the other countries, data from the World Economic Outlook (WEO) [73] were used, providing observed values up to 2024 and projections up to 2030. From 2031 onwards, a dampened growth rate was extrapolated towards a fixed final value of 2.5%, with the exception of San Marino, for which a final growth rate of 1.0% was assumed.

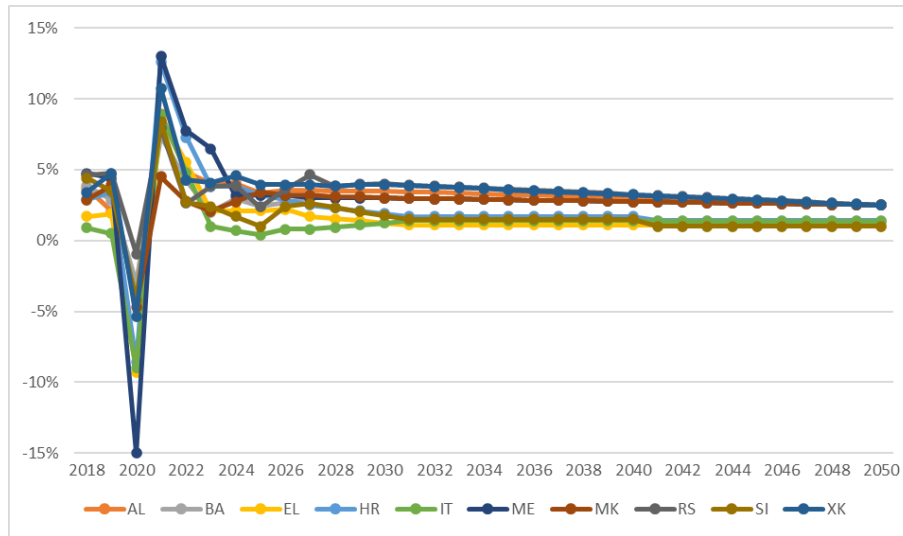


Figure 2.22: GDP forecasts for all countries of EUSAIR area

The same dataset was also used for countries outside the EUSAIR area. For the years from 2031 onwards, an extrapolation was performed using a dampened growth rate, where the damping corresponds to the reduction in growth relative to the previous year, with a minimum extrapolated growth rate of 1%.

Car Ownership Up to 2024, car ownership data are observed values and are derived from the Eurostat dataset “Passenger cars per thousand inhabitants” [60] for all countries in the study area, with the exception of San Marino. From 2025 onwards, car ownership was estimated for each country using a specific car ownership model, based on a linear estimation performed on the time-series data available up to 2024, in some cases developed for groups of countries. The model was subsequently used to generate forecasts for future time horizons by relating car ownership levels to GDP per capita projections. A saturation level for car ownership was also taken into account.

In particular, countries were grouped as follows to develop for each group its model:

1. Albania
2. Bosnia and Herzegovina, Greece and Slovenia
3. Croatia, North Macedonia and Kosovo
4. Italy
5. Montenegro and Serbia

As an illustrative example, the procedure adopted for the fifth group is briefly outlined below.

group5	ME, RS
Saturation level (car+trucks)	625

Year	COUNTRY	GDP per capita	Car ownership	Link	Model
2005	ME	14,056	194	0.80	216.61
2006	ME	15,245	249	0.41	235.24
2007	ME	16,307	290	0.14	252.38
2008	ME	17,399	304	0.05	270.41
2009	ME	16,320	288	0.16	252.59
2010	ME	16,747	266	0.30	259.59
2011	ME	17,290	277	0.23	268.60
2012	ME	16,831	284	0.18	260.99
2013	ME	17,369	288	0.16	269.90
2014	ME	17,747	280	0.21	276.22
2015	ME	18,169	283	0.19	283.29
2016	ME	18,772	297	0.10	293.47
2017	ME	19,357	310	0.02	303.37
2018	ME	20,611	332	-0.12	324.64
2019	ME	22,798	350	-0.24	361.35
2020	ME	19,572	338	-0.16	307.02
2021	ME	21,896	358	-0.29	346.31
2022	ME	23,645	369	-0.37	375.26
2023	ME	25,180	389	-0.50	399.78
2024	ME	25,964	417	-0.70	411.89
2005	RS	13,407	199	0.76	206.76
2006	RS	13,985	204	0.72	215.53
2007	RS	15,142	201	0.75	233.59
2008	RS	15,991	203	0.73	247.23
2009	RS	15,551	225	0.58	240.12
2010	RS	15,865	216	0.64	245.19
2011	RS	15,994	232	0.53	247.28
2012	RS	16,000	240	0.47	247.39
2013	RS	16,151	247	0.43	249.83
2014	RS	15,937	252	0.39	246.35
2015	RS	16,226	259	0.35	251.06
2016	RS	16,797	268	0.29	260.42
2017	RS	17,285	281	0.20	268.51
2018	RS	18,055	287	0.16	281.39
2019	RS	19,799	301	0.07	310.87
2020	RS	19,941	315	-0.02	313.27
2021	RS	21,482	329	-0.11	339.35
2022	RS	22,609	352	-0.25	358.21
2023	RS	23,625	362	-0.32	374.93
2024	RS	24,716	377	-0.42	392.48

linear estimation y=mx+b			
m	scale parameter	base parameter	b
std.err m	0.00010859	2.15039725	std.err b
R ²	0.897239254	0.12239384	std.err yesim
F-stat	331.79101	38	
ssreg	4.970312898	0.56924957	ssresid

Figure 2.23: Car Ownership Model for Montenegro and Serbia

A linear estimation is performed between the dependent variable y , representing car ownership, and the independent variable x , denoted as LINK, which is defined as follows:

$$LINK = \ln \left(\frac{1 - \frac{\text{Car Ownership}}{\text{Saturation Level}}}{\frac{\text{Car Ownership}}{\text{Saturation Level}}} \right) \quad (2.7)$$

Therefore, the value of car ownership estimated by the model corresponds to:

$$\widehat{\text{Car Ownership}} = \frac{\text{Saturation Level}}{1 + \exp(m \cdot \text{GDP per capita} + b)} \quad (2.8)$$

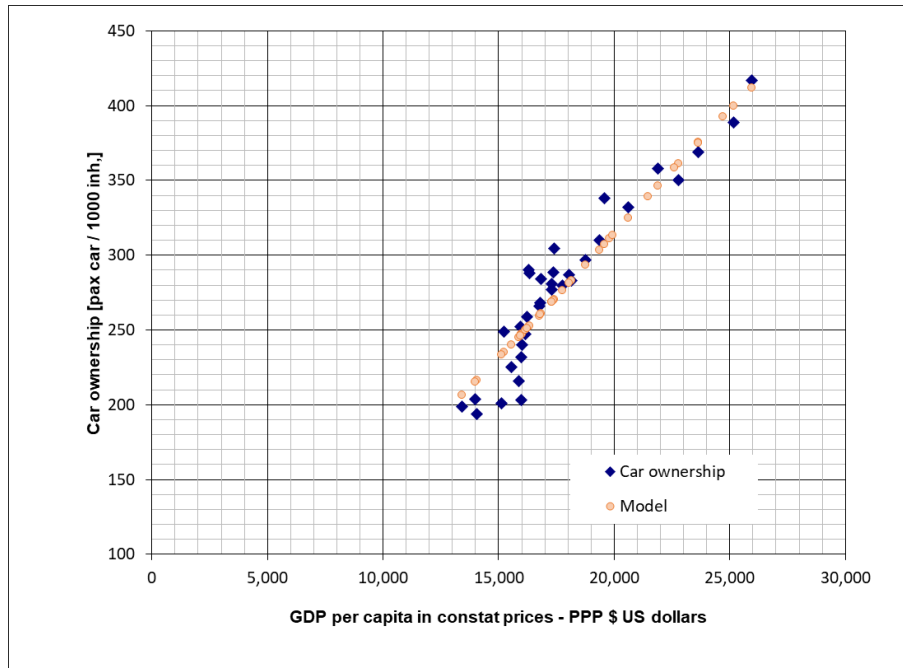


Figure 2.24: Car Ownership model for Montenegro and Serbia - observed vs estimates values

Finally, for data from 2025 onwards, the growth rate estimated by the model is applied on a year-by-year basis up to 2050.

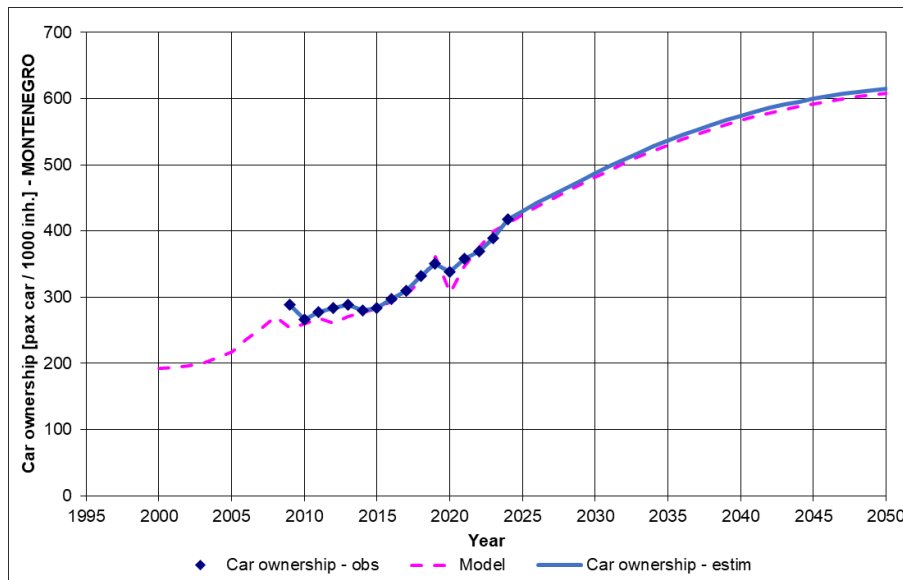


Figure 2.25: Car Ownership observed and estimated in Montenegro

In the cases of Albania and Italy, a damping mechanism was applied to the model in order to prevent the saturation level from being exceeded.

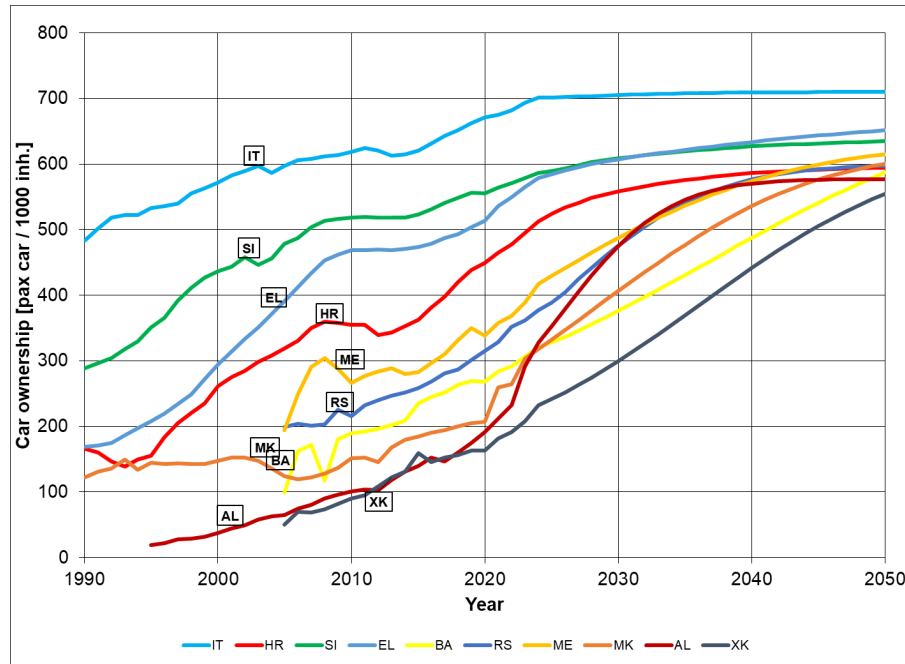


Figure 2.26: Car Ownership observed and estimated - All countries

Rail Service A Time Interval indicator was also introduced to account for the quality of rail services across the model zones. This indicator represents a proxy measure of the average headway between train pairs. For each scenario, a category ranging from 1 to 5 is assigned to each zone by comparing the average country-level link type with the link type of the zone itself. If a zone is characterised by a better level of service than the national average, it is assigned to one of the first two categories; if it is consistent with the national average, it is assigned to the third category; whereas zones with a lower level of service are assigned to the last two categories. In order to assign numerical values to the five categories, a reference category is first identified for each country. Starting from the values calculated for 2017, an average adjustment factor is applied to account for changes in both passenger-kilometres and train-kilometres between 2017 and 2023 [71]. The table below reports, for each country, the reference time interval, the reference link type and the corresponding values assumed by the time interval for each category in 2023.

Table 2.35: Reference time intervals and linktype by macro-group for year 2023

MC_GROUP	REF TIME INTERVAL	REF LINK TYPE	TIME INT cat1	TIME INT cat2	TIME INT cat3	TIME INT cat4	TIME INT cat5
AL	1240.87	74	620.4	930.7	1240.9	1861.3	2481.7
BA	376.57	61	188.3	282.4	376.6	564.8	753.1
EL	155.96	34	78.0	117.0	156.0	233.9	311.9
HR	86.42	63	43.2	64.8	86.4	129.6	172.8
ME	146.92	63	73.5	110.2	146.9	220.4	293.8
XK	3525.21	64	1762.6	2643.9	3525.2	5287.8	7050.4
RS	146.66	64	73.3	110.0	146.7	220.0	293.3
SI	59.64	53	29.8	44.7	59.6	89.5	119.3
IT_NW	29.59	33	14.8	22.2	29.6	44.4	59.2
IT_SUD	29.59	33	14.8	22.2	29.6	44.4	59.2
IT_ISL	29.59	33	14.8	22.2	29.6	44.4	59.2
IT_NE	29.59	33	14.8	22.2	29.6	44.4	59.2
IT_CNT	29.59	33	14.8	22.2	29.6	44.4	59.2
MK	566.86	53	283.4	425.1	566.9	850.3	1133.7
TR_1	115.28	87	57.6	86.5	115.3	172.9	230.6
TR_2	115.28	87	57.6	86.5	115.3	172.9	230.6
TR_3	115.28	87	57.6	86.5	115.3	172.9	230.6
BG	99.55	87	49.8	74.7	99.6	149.3	199.1
RO	99.04	87	49.5	74.3	99.0	148.6	198.1
HU	49.87	87	24.9	37.4	49.9	74.8	99.7
AT	25.39	83	12.7	19.0	25.4	38.1	50.8
CH	15.51	83	7.8	11.6	15.5	23.3	31.0
E_EUR	59.37	87	29.7	44.5	59.4	89.1	118.7
DE	27.90	83	14.0	20.9	27.9	41.9	55.8
W_EUR	46.17	83	23.1	34.6	46.2	69.3	92.3
BALT	175.21	87	87.6	131.4	175.2	262.8	350.4
SKAND	55.66	83	27.8	41.7	55.7	83.5	111.3
BE_NL_LU	12.62	83	6.3	9.5	12.6	18.9	25.2
GBR	20.88	83	10.4	15.7	20.9	31.3	41.8
XX	71.92	87	36.0	53.9	71.9	107.9	143.8

2.3. Methodology

The methodology adopted for the implementation of the EUSAIR Multimodal Transport Model (EMTM), originally developed for the 2017 base year and now updated to 2023, follows the steps described below. With regard to the four-step modelling framework [81], the trip generation and attraction stages were not implemented within the Cube environment. The modal split component is implemented as follows:

1. Passenger Transport: an absolute Logit model is applied to represent the choice between rail, road and bus modes. Model parameters are differentiated between short- and long-distance trips. Short-distance trips are defined as those occurring within the same macro-group (MC_GROUP, see Subsection 2.2.1), while long-distance trips refer to trips between different macro-groups.

Following the basic assumptions of random utility theory [81], the systematic utility functions for each mode in the passenger modal split model are defined as follows:

$$\begin{aligned}
 V_{RAIL} = & \beta_{\text{time_RAIL}} \cdot (\text{time}_{RAIL} - \text{time}_{ROAD}) \\
 & + \beta_{IJ_TIME_INT} \cdot IJ_time_int_{RAIL} \\
 & + \beta_{car_own_RAIL} \cdot car_own + COEFF_IJ_RAIL
 \end{aligned} \tag{2.9}$$

$$\begin{aligned}
 V_{BUS} = & \beta_{\text{time_BUS}} \cdot (\text{time}_{BUS} - \text{time}_{ROAD}) \\
 & + \beta_{car_own_BUS} \cdot car_own + COEFF_IJ_BUS
 \end{aligned} \tag{2.10}$$

$$V_{ROAD} = COEFF_IJ_ROAD \tag{2.11}$$

2. Freight transport: an absolute Logit model is applied to represent the choice between rail and road modes.

Generalised costs are defined as follows:

$$\begin{aligned}
GC_{\text{RAIL}} = & COST_{\text{tonn,RAIL}} \\
& + \frac{PORT_{\text{ZONE}} \cdot \beta_{\text{port}}^{\text{FREIGHT}} - \left(COEFF_I^{\text{FREIGHT}} + COEFF_J^{\text{FREIGHT}} + COEFF_{IJ}^{\text{FREIGHT}} \right)}{\beta_{\text{cost}}^{\text{FREIGHT}}}
\end{aligned}
\tag{2.12}$$

$$GC_{\text{ROAD}} = COST_{\text{tonn_ROAD}} \tag{2.13}$$

It should be noted that, within the road mode, different vehicle categories are distinguished: cars, buses, heavy goods vehicles (HGVs) and light goods vehicles (LGVs). The LGV demand matrix is developed outside the Cube environment and subsequently integrated into the model.

For the actual update of the model, the following steps were carried out:

1. **Update of total demand matrices:** total passenger and freight matrices for all modes were updated using a Fratar (growth factor) procedure with fixed margins, applying country-specific growth factors, as shown in Figure 2.20.
2. **Recalculation of prior modal matrices:** prior modal matrices were then recalculated by applying the modal split model calibrated in the previous version of the model. This procedure produced prior passenger matrices by mode (road, rail and bus), expressed both in passengers and in vehicles through the application of mode-specific occupancy factors. Similarly, prior freight matrices by mode (road and rail) were obtained, expressed in tonnes and converted into heavy goods vehicles (HGVs) using appropriate load factors and empty-vehicle shares.
3. **Adjustment of modal matrices:** finally, the prior modal matrices were adjusted to ensure consistency with observed data and modelling assumptions.

Table 2.36 reports the main key parameters used in the model, with particular reference to the updated 2023 Base Year scenario.

Table 2.36: Key parameters used in the model

Key Value	Value	Unit
Year	2023	[]
Zones	364	[]
Expansion coefficient	14	[hours/day]
VoT_{LGV}	34.2	[€/hour]
VoT_{HGV}	66.4	[€/hour]
HGV equivalence coefficient	2.5	[veh _{HGV} /veh _{CAR}]
LGV equivalence coefficient	1.5	[veh _{LGV} /veh _{CAR}]
BUS equivalence coefficient	1.5	[veh _{BUS} /veh _{CAR}]
Operative Costs HGV	0.50	[€/km]
Operative Costs LGV	0.24	[€/km]
Operative Costs RAIL km	0.0079	[€/(t-km)]
Operative Costs RAIL h	1.1106	[€/(t-hour)]
Operative Costs RAIL fixed	2.9866	[€/t]
Total Terminalization Costs RAIL	11	[€/t]
Unit Load HGV EUSAIR	16	[t/veh _{HGV}]
Unit Load HGV External EUSAIR	18	[t/veh _{HGV}]
Empty Share HGV EUSAIR	0.2	[]
Empty Share HGV External EUSAIR	0.1	[]
$\beta_{cost}^{FREIGHT}$	0.0757	[]
$\beta_{port}^{FREIGHT}$	-1.0763	[]
$VoT_{meanCAR}$	18.1	[€/hour]
VoT_{IT}	19.4	[€/hour]
VoT_{EU}	15.4	[€/hour]
VoT_{NON-EU}	13.8	[€/hour]

2.3.1. Assignment Model

The assignment model is implemented as follows:

1. For ROAD (CAR/BUS/LGV/HGV, including roll-on/roll-off), a stochastic path

choice model with Burrell’s uniform cost function was chosen, which returns matrices referring to the average hour of the average day, with a daily expansion coefficient of 14 hours/day and an annual expansion coefficient of 365, for vehicles and passengers and for goods in thousands of tonnes per year. The system is congested.

2. For both passenger and freight rail transport, a deterministic All-or-Nothing (AoN) assignment is applied. The resulting outputs consist of passenger matrices referring to the average hour of a representative weekday and freight matrices expressed in thousand tonnes per year.

2.3.2. Model Calibration

Using the traffic count data collected (see 2.2.3), the model calibration process was carried out, adjusting primarily the prior matrices for road vehicles. During this phase, targeted demand adjustments were also applied to the rail freight matrix where necessary.

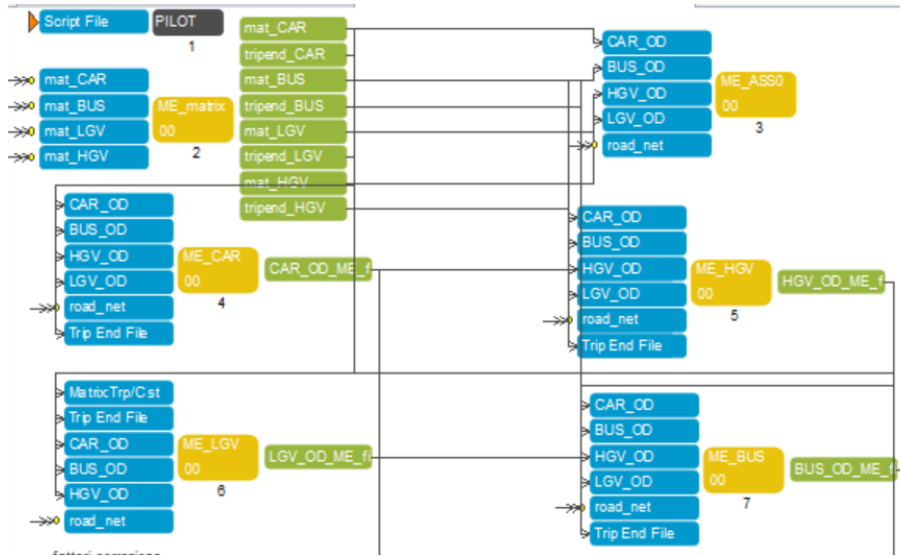


Figure 2.27: Model Calibration APP in *Cube*

First, confidence levels are assigned to the initial demand matrices. Subsequently, following a “zero” assignment (performed using the procedures illustrated in Subsection 2.3.1), the correction blocks are applied for each road vehicle segment, starting with cars, for which traffic counts are more accurate and numerous, and progressing to buses, which are characterised by a limited availability of traffic counts across the countries in the study area.

The main tool used to perform this calibration for each mode is the *Analyst* module within *Cube*. To achieve an optimal calibration outcome,

1. targeted adjustments to the network are implemented
2. some traffic counts may be excluded where necessary or aggregated (for instance, when a motorway section runs parallel to a lower-capacity road section)
3. localised demand adjustments may also be applied to specific links or groups of links.

The results obtained for each road segment are illustrated below through scatter plots.

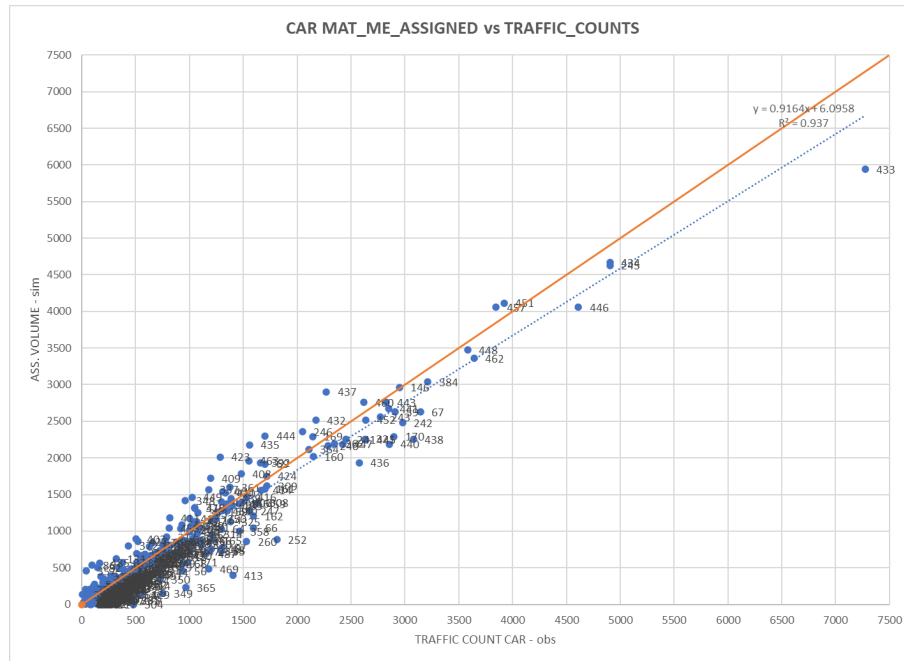


Figure 2.28: CAR - Simulated traffic flows VS Observed traffic counts

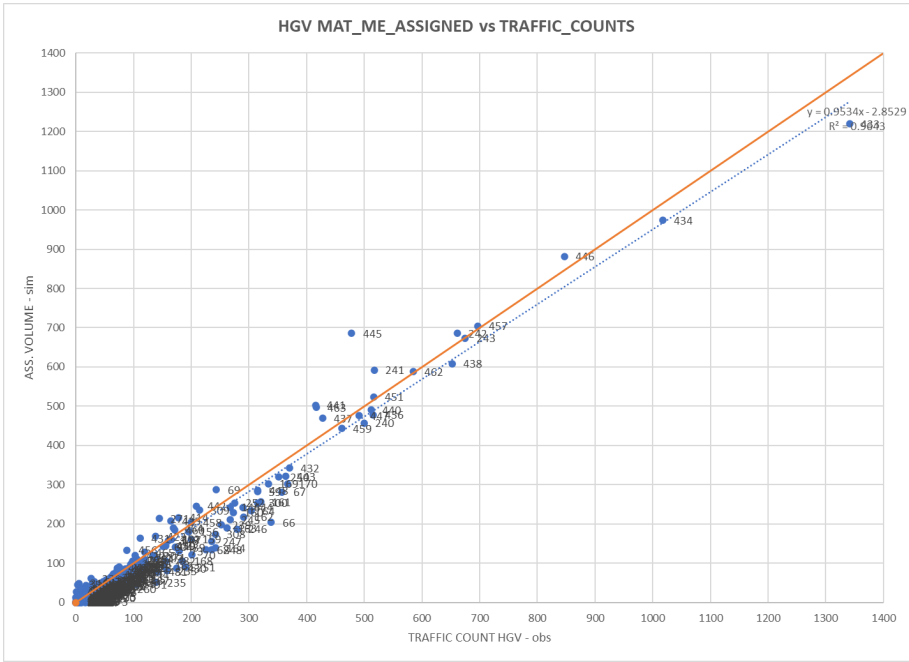


Figure 2.29: HGV - Simulated traffic flows VS Observed traffic counts

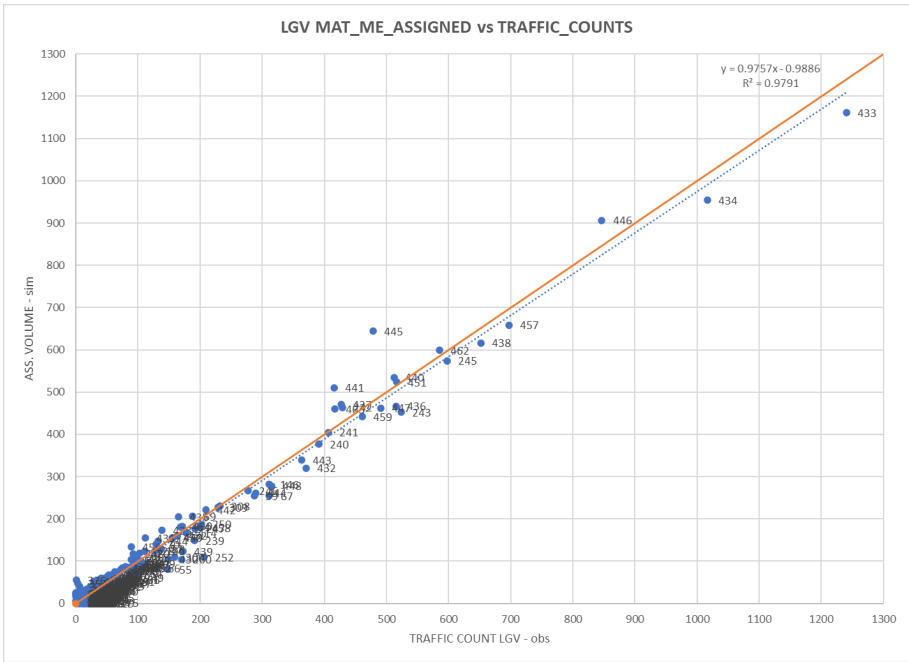


Figure 2.30: LGV - Simulated traffic flows VS Observed traffic counts

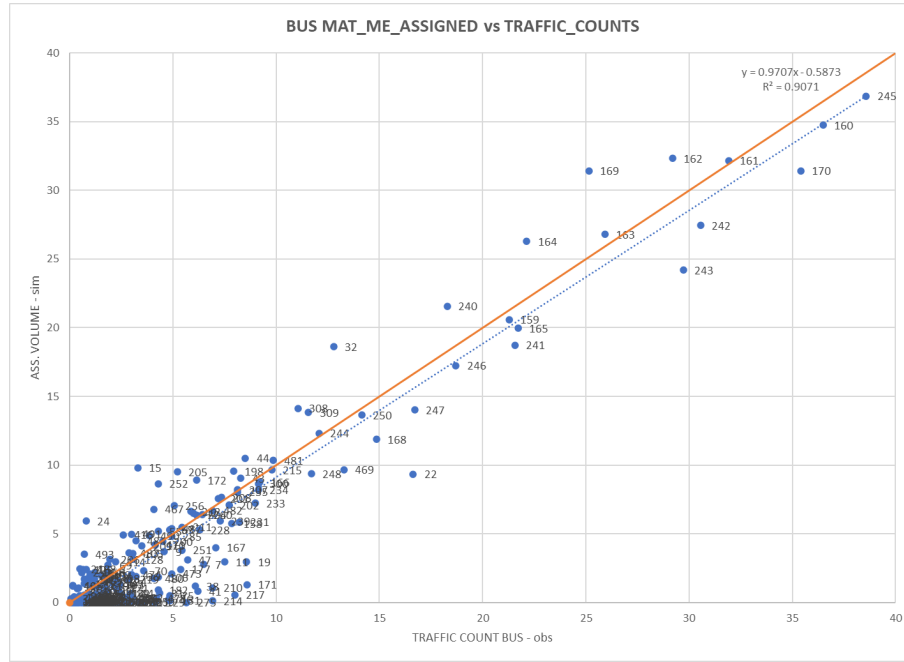


Figure 2.31: BUS - Simulated traffic flows VS Observed traffic counts

The R^2 values identified for each vehicle category are as follows:

1. $R^2_{\text{CAR}} \approx 0.94$
2. $R^2_{\text{HGV}} \approx 0.97$
3. $R^2_{\text{LGV}} \approx 0.98$
4. $R^2_{\text{BUS}} \approx 0.91$

These results indicate a very good correspondance between observed traffic volumes and those simulated by the model. In particular, the calibration for LGVs, HGVs and cars proves to be very effective, also benefiting from the greater availability and higher quality of vehicle classification in traffic count data. The BUS segment exhibits a more scattered pattern, which is reflected in a slightly lower R^2 value. This behaviour is attributable both to the way the bus demand matrix was constructed and to the limited availability of traffic count data for this vehicle category, as well as to the generally lower traffic volumes. However, the calibration results for the BUS segment remain satisfactory within the overall modelling framework.

Once the corrected matrices were obtained, correction factors were computed, as the ratio between the new calibrated matrices and the "old" prior modal ones. Then, they were applied to the prior modal matrices. Where necessary, the factors were capped to ensure that the matrices did not deviate excessively from the prior ones.

3 | Indicators for supranational multimodal transport models: state of the art and application to the EUSAIR case study

This chapter presents the state of the art of multimodal transport models, with a particular focus on supranational scale and on the indicators commonly used for their evaluation. The review of indicators aims to identify the most suitable ones, also with reference to the application developed in this thesis. In the second part of the chapter, the outcomes of the application to the EUSAIR case study are presented and discussed. Selected indicators are applied in order to provide additional insights into the performance of the multimodal transport model.

3.1. State of the Art and Supranational Indicators

Multimodal transport models at the macro level or at the supranational scale, can be classified according to the methodological approach on which they are based.

A first relevant example is TRANS-TOOLS (TOOLS for Transport forecasting ANd Scenario testing), a European transport network model originally developed starting from 2004 and subsequently updated until its third version released in 2014. TRANS-TOOLS is a multimodal transport model covering the countries of the former EU-25. It is defined as a network-based model, as it explicitly represents transport networks and performs traffic assignment procedures in order to compute link flows and related network performance indicators, such as travel times, costs and congestion levels [82].

Another example of a supranational transport model is HIGH-TOOL (High-Level Strategic Transport Model). Compared to network-based models such as TRANS-TOOLS, HIGH-TOOL relies on a less detailed representation of the transport network, which allows for faster computation times and makes the model particularly suitable for policy

assessment. Rather than performing detailed traffic assignment on transport networks, HIGH-TOOL is structured around a set of core modules that define the modelling framework, a database that facilitates data exchange and a user interface for the model application and access to results. Several modules are based on ETISplus data. For instance, within the passenger demand module, origin-destination matrices are computed using trip rate factors derived from ETISplus, while passenger-kilometres and vehicle-kilometres are estimated using travel distances and occupancy rates provided by the same database. As a consequence, HIGH-TOOL does not provide a detailed representation of network performance at the link level. However, at a higher level, the model allows the evaluation of policy impacts on transport demand, modal split, environmental effects and economic indicators [83].

Beyond transport models in a strict sense, several studies and research projects focus specifically on accessibility, which is one of the most widely used indicators in territorial-based transport evaluations. An example is the ESPON project TRACC (TRansport ACCessibility at regional/local scale and patterns in Europe), whose objective is to analyse, systematise and compare different accessibility indicators, taking into account also emerging challenges at the regional and supranational level. Accessibility is defined within the project as follows:

“Indicators of accessibility measure the benefits households and firms in an area enjoy from the existence and use of the transport infrastructure relevant for their area.”

Within the TRACC framework, three main types of accessibility indicators are identified:

1. Travel cost (to a set of activities)
2. Cumulated opportunities, defined as the number of activities that can be reached within a given travel time
3. Potential accessibility, where activities are weighted by a function of travel cost.

Based on the literature review carried out within the project, a wide range of accessibility indicators is further developed, primarily distinguished according to the spatial context considered: global, European and regional scales. For instance, with respect to European travel accessibility, one of the proposed indicators is “daily accessibility by fastest mode”, defined as the number of persons living in other European regions that can be reached within a one-way travel time of five hours. In addition, potential accessibility to population is computed for three transport modes (road, rail and air), as well as for their combined use in a multimodal framework. The resulting accessibility indicators are

standardised with respect to the ESPON average, which is set equal to 100 [84].

For multimodal transport models, one of the most relevant demand-related indicators is modal split, which is also widely used and discussed within Eurostat statistics and monitoring activities. According to the definition provided by Eurostat, “Modal split measures the composition of transport performance, meaning the importance of each mode of transport in total freight or passenger transport. It is defined as the percentage of each mode of transport in total transport performance” [85].

With regard to network performance indicators, although they are generally more relevant in urban-scale models, indicators such as the volume-to-capacity (V/C) ratio can also provide useful insights in network-based multimodal models. In particular, the V/C ratio can serve as an indicator of areas or infrastructure sections characterised by higher levels of congestion and saturation, especially when traffic assignment procedures are explicitly applied.

In addition to traditional transport-related indicators, multimodal transport models can be used also to evaluate complementary dimensions of transport systems. In particular, environmental impacts can be assessed through the estimation of CO₂ emissions, potentially disaggregated by transport mode, while safety-related aspects can be analysed by quantifying expected numbers of accidents and fatalities.

3.2. Application to the EUSAIR Case Study (EUSAIR Multimodal Transport Model)

Based on the methodological framework described in Chapter 2 and on the review of indicators presented in the previous section 3.1, this section analyses the results of the application of the EUSAIR Multimodal Transport Model (EMTM) for the year 2023.

The indicators selected to assess the model include:

1. the modal split, which is essential for understanding how passenger and freight flows are distributed among the different transport modes
2. the Interconnectivity Quality Index, providing a specific focus on the quality and performance of transport infrastructure
3. accessibility indicators for passenger transport, computed with respect to both population and employment.

Starting from the traffic assignment performed on the transport rail and road networks,

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passenger and freight base year daily flows can first be derived and analysed.

The following maps present the flow diagrams for ROAD and RAIL passenger transport, expressed in passengers per day.



Figure 3.1: CAR Passenger Transport - Flow bandwidth [PAX/DAY]



Figure 3.2: BUS/COACH Passenger Transport - Flow bandwidth [PAX/DAY]



Figure 3.3: Rail Passenger Transport - Flow bandwidth: PAX/DAY

These initial results show that passenger flows are higher in Italy than in the other countries of the study area for both road and rail transport, with a particularly marked difference in the case of rail.

With regard to freight transport, the following maps present the flow diagrams for road and rail, expressed in tonnes per day.

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Figure 3.4: Road Freight Transport - Flow bandwidth: TONN/DAY



Figure 3.5: Rail Freight Transport - Flow bandwidth: TONN/DAY

Overall, the results of freight transport are broadly consistent with those observed for passenger transport. Slovenia stands out for higher traffic volumes among the Western Balkan countries, particularly the difference is higher in rail transport.

Transport Performance and Modal Split

One of the most important indicators in multimodal transport models is the modal split. In order to compute it, it is necessary to start from transport performance, expressed in terms of passenger-kilometres and tonne-kilometres for each transport segment.

The following tables are differentiated by country within the study area. It should be noted that for Italy the results refer to the country as a whole. Where available, the model results are compared with the statistics reported in the European Commission Statistical Pocketbook 2025 [71].

Table 3.1: CAR Passenger-kilometres transport performance by country [billion pkm]

Country	PAXKM_MODEL	PAXKM_POCKETBOOK_2023	PAXKM_ratio
AL	15.383	15.795	0.974
BA	27.638	n.a.	
EL	108.192	109.407	0.989
HR	41.406	24.033	1.723
ME	5.476	5.451	1.005
XK	8.982	n.a.	
RS	41.560	34.298	1.212
SI	26.878	24.741	1.086
IT	766.881	674.190	1.137
MK	10.854	12.480	0.870
EUSAIR	1053.251		

Table 3.2: BUS/COACH Passenger-kilometres transport performance by country [billion pkm]

Country	PAXKM_MODEL	PAXKM_POCKETBOOK_2023	PAXKM_ratio
AL	4.684	1.443	3.247
BA	3.887	1.376	2.824
EL	15.596	18.906	0.825
HR	6.708	3.480	1.928
ME	0.805	0.052	15.472
XK	1.310	n.a.	
RS	11.631	4.740	2.454
SI	4.004	3.448	1.161
IT	75.537	80.841	0.934
MK	1.283	1.010	1.271
EUSAIR	125.444		

Table 3.3: RAIL Passenger-kilometres transport performance by country [billion pkm]

Country	PAXKM_MODEL	PAXKM_POCKETBOOK_2023	PAXKM_ratio
AL	0.001	0.0004	2.246
BA	0.041	0.0340	1.202
EL	0.628	0.6730	0.934
HR	1.036	1.1420	0.907
ME	0.053	0.0678	0.786
XK	0.014	n.a.	
RS	0.499	0.5280	0.945
SI	0.651	0.7420	0.878
IT	59.196	54.7910	1.080
MK	0.041	0.0320	1.273
EUSAIR	62.160		

Considering all passenger transport modes together, the modal split results are reported below.

Table 3.4: Passenger transport modal split by country

Country	PAX-KM modal split (RAIL–CAR–BUS)					
	RAIL_M	BUS_M	CAR_M	RAIL_PB2023	BUS_PB2023	CAR_PB2023
AL	0.0%	23.3%	76.7%	0.0%	8.4%	91.6%
BA	0.1%	12.3%	87.6%	n.a.	n.a.	n.a.
EL	0.5%	12.5%	87.0%	0.5%	14.7%	84.8%
HR	2.1%	13.6%	84.2%	4.0%	12.1%	83.9%
ME	0.8%	12.7%	86.5%	1.2%	0.9%	97.8%
XK	0.1%	12.7%	87.1%	n.a.	n.a.	n.a.
RS	0.9%	21.7%	77.4%	1.3%	12.0%	86.7%
SI	2.1%	12.7%	85.2%	2.6%	11.9%	85.5%
IT	6.6%	8.4%	85.1%	6.8%	10.0%	83.3%
MK	0.3%	10.5%	89.1%	0.2%	7.5%	92.3%
EUSAIR	5.0%	10.1%	84.9%			

The results estimated by the model and those reported in the Statistical Pocketbook are overall highly comparable. Some deviations are observed in bus and coach transport performance. However, these differences are mainly attributable to the construction and calibration of the corresponding matrix, as well as to the presence of outliers in the historical data series.

Similarly, the same set of tables is presented for freight transport.

Table 3.5: ROAD Tonne-kilometres transport performance by country [billion tkm]

Country	TKM_MODEL	TKM_POCKETBOOK_2023	TKM_ratio
AL	2.825	n.a.	
BA	5.159	n.a.	
EL	17.456	18.130	0.963
HR	16.118	10.197	1.581
ME	1.352	n.a.	
XK	0.834	n.a.	
RS	16.324	n.a.	
SI	14.814	9.335	1.587
IT	174.867	166.164	1.052
MK	3.063	n.a.	
EUSAIR	252.812		

Table 3.6: RAIL Tonne-kilometres transport performance by country [billion tkm]

Country	TKM_MODEL	TKM_POCKETBOOK_2023	TKM_ratio
AL	0.031	0.019	1.636
BA	1.497	1.262	1.186
EL	0.198	0.211	0.940
HR	2.954	3.145	0.939
ME	0.172	0.163	1.055
XK	0.111	n.a.	
RS	2.269	2.124	1.068
SI	5.240	4.629	1.132
IT	27.350	22.693	1.205
MK	0.141	0.146	0.965
EUSAIR	39.964		

Table 3.7: Freight transport modal split by country (rail and road)

Country	T-KM modal split			
	RAIL_M	ROAD_M	RAIL_PB2023	ROAD_PB2023
AL	1.1%	98.9%	n.a.	n.a.
BA	22.5%	77.5%	n.a.	n.a.
EL	1.1%	98.9%	1.2%	98.8%
HR	15.5%	84.5%	23.6%	76.4%
ME	11.3%	88.7%	n.a.	n.a.
XK	11.7%	88.3%	n.a.	n.a.
RS	12.2%	87.8%	n.a.	n.a.
SI	26.1%	73.9%	33.1%	66.9%
IT	13.5%	86.5%	12.0%	88.0%
MK	4.4%	95.6%	n.a.	n.a.
EUSAIR	13.6%	86.4%		

For freight transport as well, a comparison of the results is possible, particularly for rail transport, for which data are available for all countries in the study area.

Taking an overall look at the modal split results, the results clearly show the dominant contribution of Italy to transport performance within the EUSAIR area, both for passenger and freight transport, especially for rail. This outcome is not unexpected, as Italy represents the largest country in the study area in terms of territorial extension, population and economic activity. Consequently, its transport performance is significantly higher than that of the other EUSAIR countries.

With regard to countries for which official reference data are partially or entirely unavailable (see in particular ROAD tonne-kilometres in Table 3.6), the model outputs still appear reasonable and internally consistent. The estimated transport performance values are in line with those obtained for the 2017 base year, which were previously validated, where possible, against UNECE datasets. Moreover, the differences observed across countries are broadly consistent with their relative demographic and economic profiles. For example, Serbia exhibits higher transport performance levels than Albania, North Macedonia and Montenegro, while the latter, being broadly similar in terms of size and population, show comparable values among themselves.

This internal consistency is further supported by the model calibration process, which proved useful in verifying the reliability of the results also at the national level. The

calibration ensured that aggregate traffic volumes and transport performance indicators were reasonable and balanced, increasing confidence in the acceptability of the estimated performance results even in the absence of direct statistical comparisons, such as in the case of road freight results.

Infrastructure Connectivity Indexes

Connectivity indicators are used to assess the supply side of the model. In particular, they have been computed for both road and rail transport.

The road Infrastructure Connectivity Index (ICI) is calculated as the average of the ratios between a reference travel time calculated assuming 120 km/h as reference speed for the entire road network (T_{ref}) and the simulated inter-zonal travel time on the existing networks (T_{sim}).

The index is computed for each zone with respect to all other zones within the EUSAIR region and its values range between 0 and 1. Values closer to 1 indicate a higher level of connectivity, reflecting better network quality. The equation of the Interconnectivity Quality Index (ICI), applicable to both the road and rail networks, is reported below.

$$ICI = \frac{1}{N} \sum_{i=1}^N \frac{T_i^{ref}}{T_i^{sim}} \quad (3.1)$$

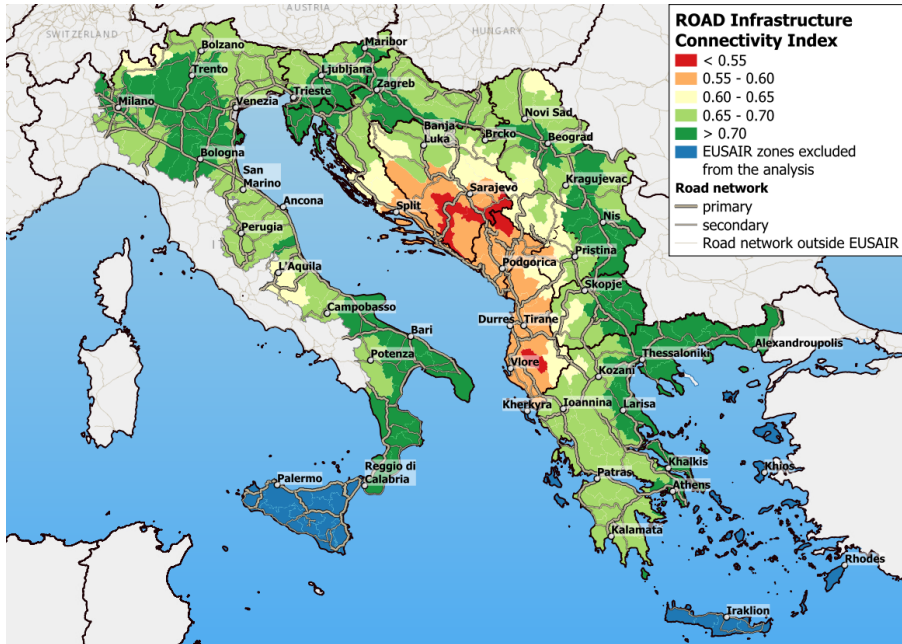


Figure 3.6: ROAD Infrastructure Connectivity Index

For the EUSAIR study area, the road Infrastructure Connectivity Index shows a relatively homogeneous spatial distribution. Most zones display ICI values concentrated within the range between 0.65 and 0.70 or exceeding it, indicating limited variability in road connectivity levels across the region. Lower values below 0.55 are mainly observed in some rural zones in Bosnia and Herzegovina and Albania.

The rail Infrastructure Connectivity Index can be computed similarly. It is defined as the average of the ratios between a reference travel time, calculated assuming a reference speed of 150 km/h over the entire rail network (T_{ref}), and the simulated inter-zonal travel time on the existing network (T_{sim}).

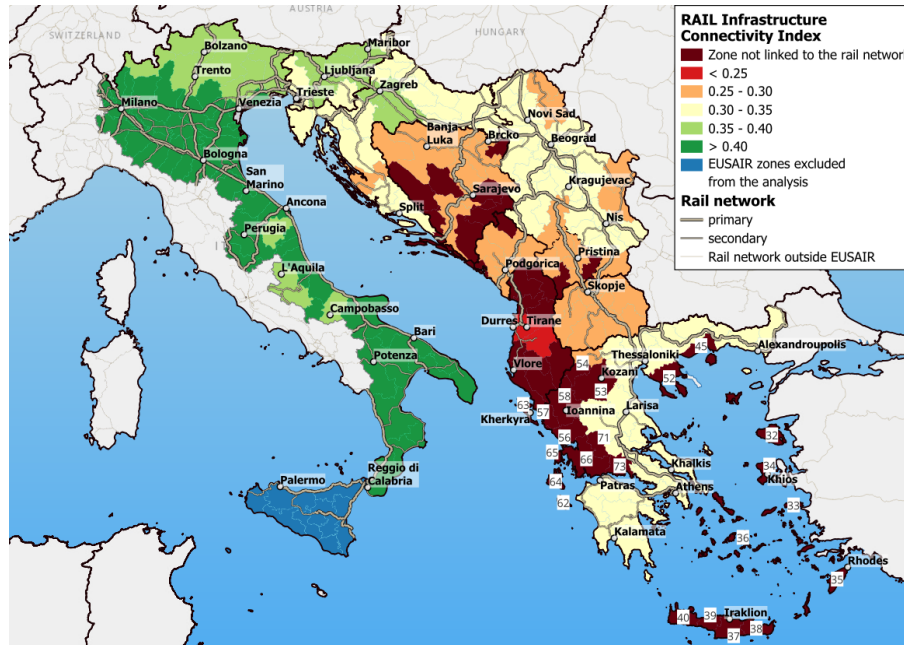


Figure 3.7: RAIL Infrastructure Connectivity Index

The rail Infrastructure Connectivity Index highlights markedly stronger spatial disparities compared to the road network. Rail connectivity values are generally lower and more unevenly distributed, with a substantial number of zones showing very limited or null connectivity due to the absence of rail infrastructure. As a result, the range of values observed for the rail ICI is significantly lower, approximately between 0.25 and 0.40, and a different classification scale was therefore adopted for representation purposes. Higher rail connectivity levels are mainly concentrated in Italy, particularly along the main national rail corridors, while large parts of the Western Balkans exhibit fragmented or discontinuous rail connectivity. In these areas, road transport represents the primary, and in some cases the only, means of territorial connection.

Islands, in particular Sicily and the Greek islands, were excluded from the analysis due to their intrinsic connectivity constraints. Given their structural dependence on maritime and air transport, the Infrastructure Connectivity Index would not adequately capture their effective accessibility conditions.

Accessibility

As already discussed in the previous state of the art review, accessibility represents a key indicator for territorial-based transport assessments, as it allows the integration of transport-related aspects with demographic, social and economic factors.

For the application to the EUSAIR Multimodal Transport Model, accessibility indicators were computed with reference to passenger transport modes. In particular, passive accessibility with respect to population and active accessibility with respect to employment were calculated, according to the equations reported below. Given the large spatial extent of the study area, travel time thresholds of 3 and 5 hours were respectively adopted as impedance values.

$$Accessibility_{\text{passive}}(d) = \sum_{i: t_{(d,i)} < 3 \text{ h}} Population(i) \quad (3.2)$$

$$Accessibility_{\text{active}}(o) = \sum_{i: t_{(o,i)} < 5 \text{ h}} Jobs(i) \quad (3.3)$$

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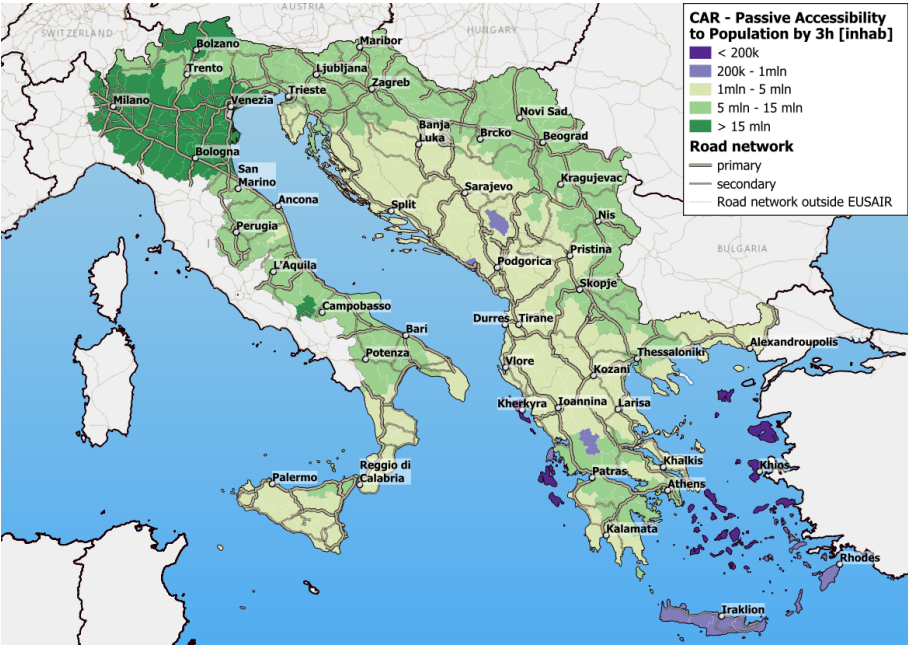


Figure 3.8: CAR - Passive Accessibility wrt. Population

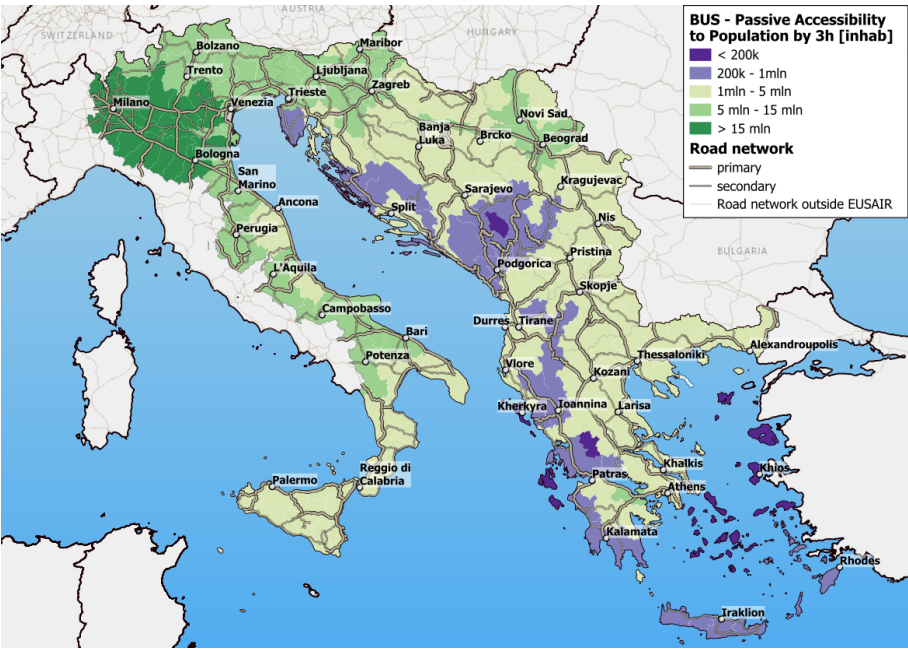


Figure 3.9: BUS - Passive Accessibility wrt. Population

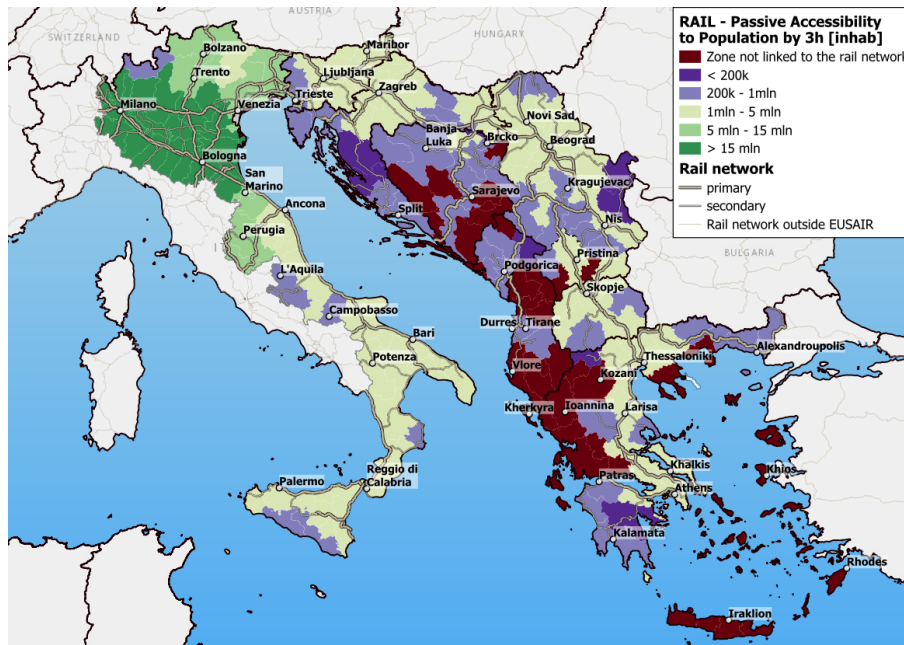


Figure 3.10: RAIL - Passive Accessibility wrt. Population

The same classification scale was adopted for all three transport modes in order to ensure comparability across the maps. The maps highlight clear differences across transport modes. Road transport by car provides the highest and most homogeneous levels of accessibility across the EUSAIR study area, while bus accessibility shows more localized patterns, mainly compensating for limited rail services. Rail accessibility is instead highly concentrated in Northern Italy, with large portions of the Western Balkans and island regions exhibiting null or very low values.

3| Indicators for supranational multimodal transport models: state of the art and application to the EUSAIR case study

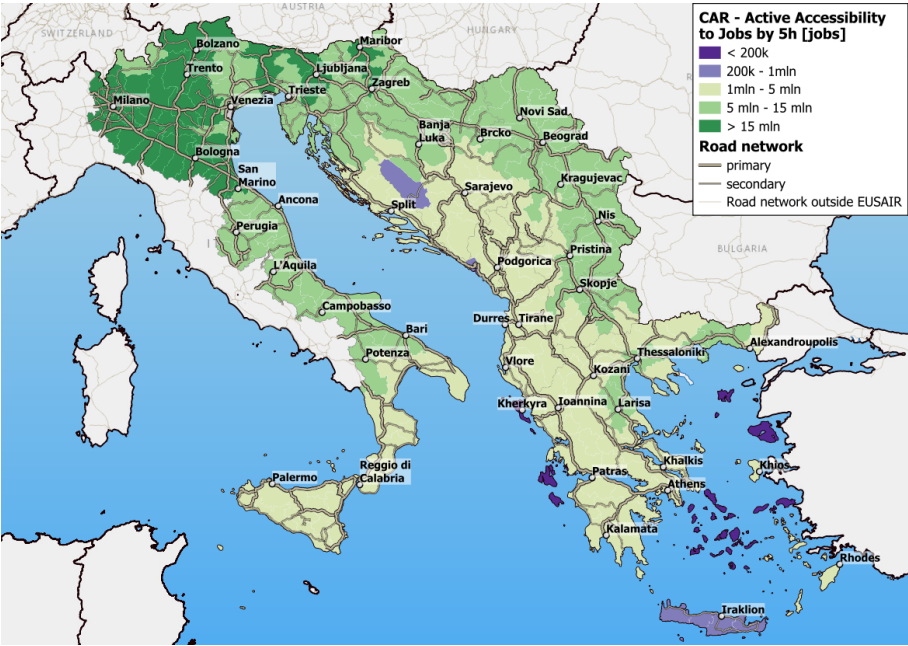


Figure 3.11: CAR - Active Accessibility wrt. Jobs

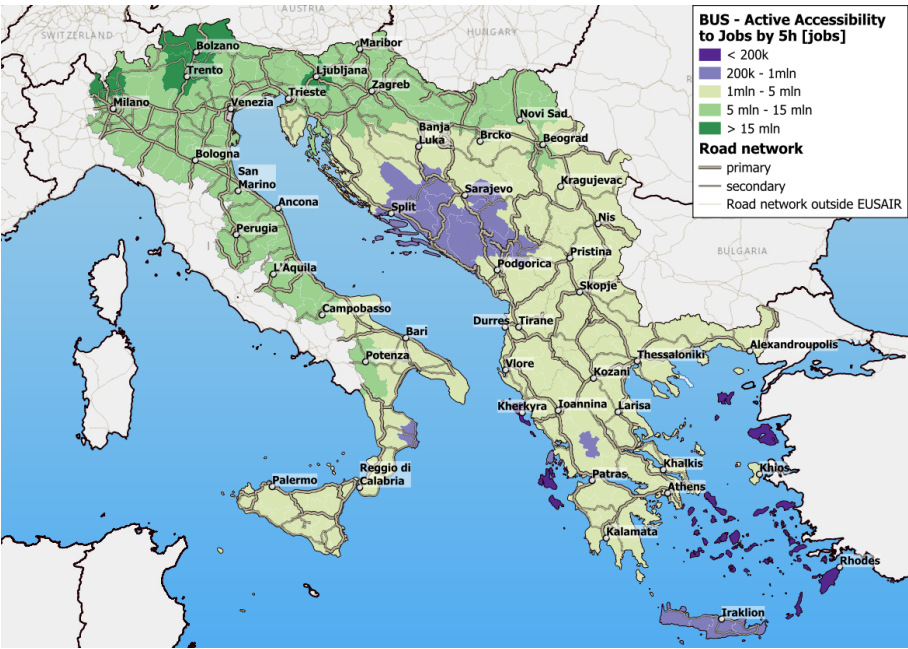


Figure 3.12: BUS - Active Accessibility wrt. Jobs

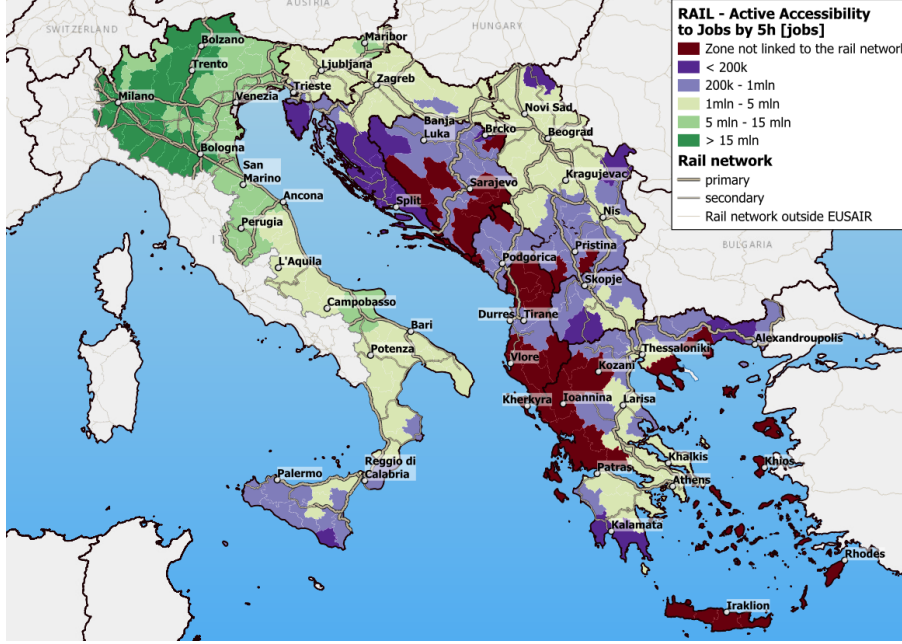


Figure 3.13: RAIL - Active Accessibility wrt. Jobs

Overall, the maps of active accessibility to jobs show information similar to that observed for population accessibility. However, an additional socio-economic dimension emerges, as some areas display lower accessibility values not only due to weaker network performance, but also because they are characterised by a lower availability of employment opportunities.

In order to illustrate the contribution of each transport mode to the accessibility levels previously computed, Accessibility Ratios were calculated for each transport mode. In particular, these ratios were computed with respect to population, according to the following formulation:

$$CAR_Accessibility_Ratio = \frac{Pass_Acc_{CAR}}{Pass_Acc_{CAR} + Pass_Acc_{BUS} + Pass_Acc_{RAIL}} \quad (3.4)$$

$$BUS_Accessibility_Ratio = \frac{Pass_Acc_{BUS}}{Pass_Acc_{CAR} + Pass_Acc_{BUS} + Pass_Acc_{RAIL}} \quad (3.5)$$

$$RAIL_Accessibility_Ratio = \frac{Pass_Acc_{RAIL}}{Pass_Acc_{CAR} + Pass_Acc_{BUS} + Pass_Acc_{RAIL}} \quad (3.6)$$

3| Indicators for supranational multimodal transport models: state of the art and application to the EUSAIR case study

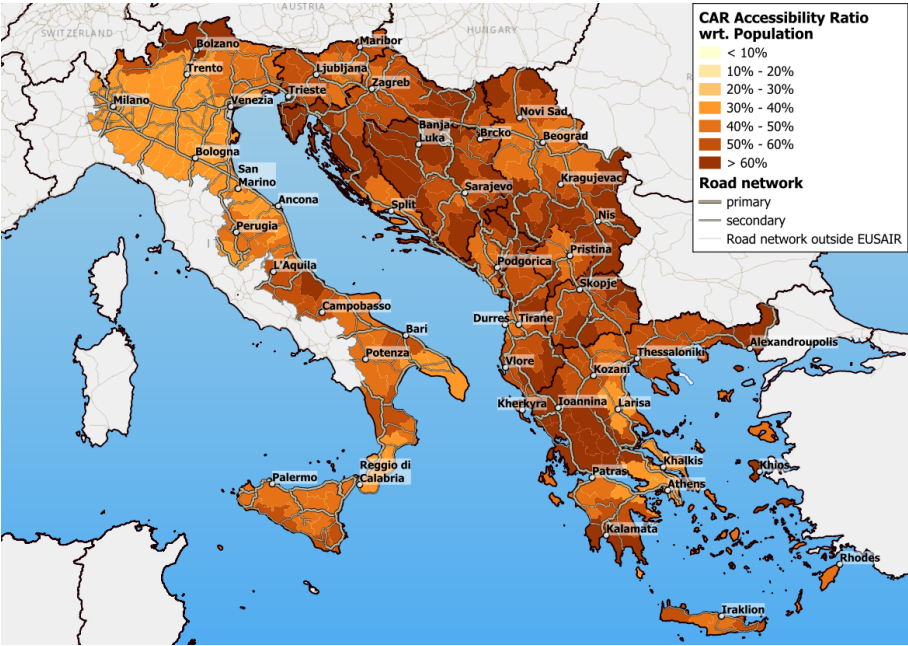


Figure 3.14: CAR Accessibility Ratio wrt. Population

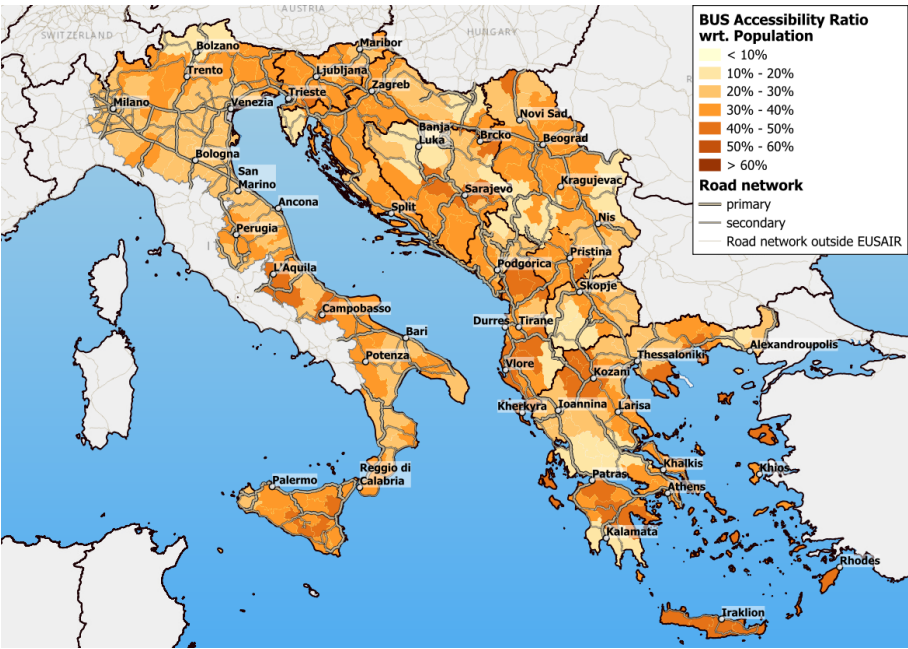


Figure 3.15: BUS Accessibility Ratio wrt. Population

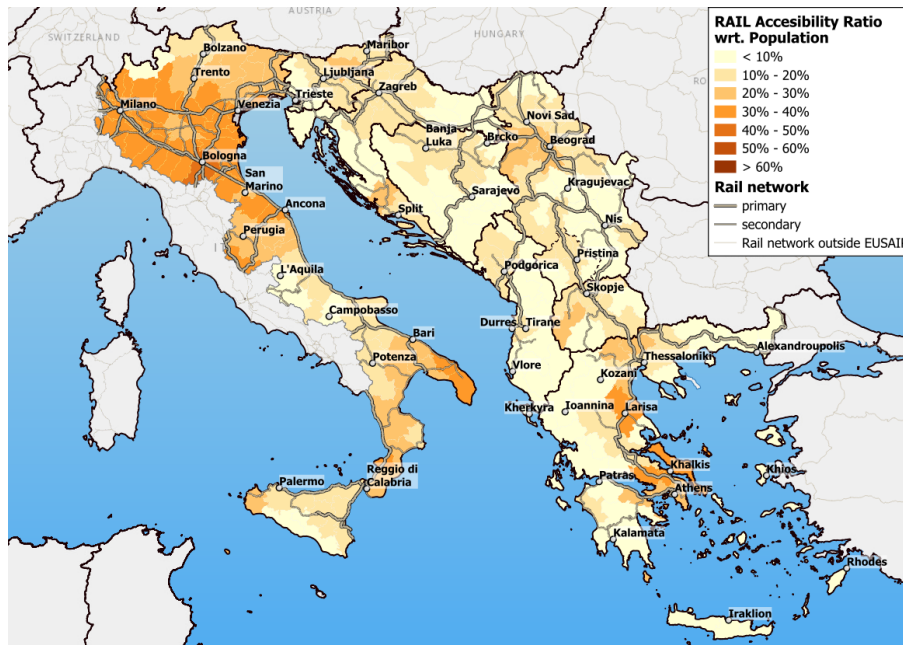


Figure 3.16: RAIL Accessibility Ratio wrt. Population

The accessibility ratio maps provide a complementary view to the absolute accessibility indicators, as they describe the relative contribution of each mode to overall passive accessibility to population. For example, the car accessibility ratio identifies areas that are more dependent on private car use to achieve population accessibility. These patterns are consistent with the modal split results for passenger transport, which show a dominant role of road-based modes across the EUSAIR area. At the same time, the rail accessibility ratio highlights a limited number of corridors and regions where rail plays a substantial role, in line with the generally lower rail shares observed in the modal split statistics.

Overall, the accessibility results highlight marked territorial disparities across the EUSAIR area, reflecting differences in structural characteristics of the transport systems and its performance. In particular, large parts of the Western Balkans show a strong dependence on road transport, with car accessibility playing a dominant role in providing access to population and employment. This contrasts with Northern Italy, where rail transport contributes significantly to accessibility levels. These patterns are closely linked to the current state of rail infrastructure across the study area. Northern Italy benefits from a relatively dense and well-developed railway network, while many regions in the Western Balkans are characterised by underdeveloped rail systems and, in some cases, by significant morphological and geographical constraints that limit the development of this kind of infrastructure and therefore the connectivity of the region. As a result, accessibility to opportunities in these areas is often effectively constrained to the private car as a single

transport mode. From a broader perspective, this modal dependence raises issues related to both equity and sustainability. Reliance on private car use may reduce accessibility for population groups without access to a car, thereby increasing inequalities, and lead to higher environmental impacts due to increased emissions. In this sense, the accessibility indicators and accessibility ratios provide useful insights not only into transport system performance, but also into potential policy challenges related to making more inclusive and sustainable the study area.

4 | Conclusions and further developments

This thesis presented the development and update to the 2023 base year of a macro-scale multimodal transport model, the EUSAIR Multimodal Transport Model (EMTM), first developed by Tplan Consulting using the *Cube* software and applied within the framework of the EU Strategy for the Adriatic and Ionian Region (EUSAIR). The Adriatic–Ionian Region represents the study area to which the model was applied in order to assess the performance of road and rail networks through a set of specific indicators, commonly adopted in the evaluation of macro-scale multimodal transport models.

The implementation of the work followed a structured methodological framework. The first phase focused on data collection and was aimed at updating the road and rail networks and parameters to the year 2023, including all relevant infrastructure investments completed between 2017, the base year of the previous model version, and 2023. Subsequently, socioeconomic data were updated, representing a fundamental element both for understanding social and economic disparities across the study area and for modelling transport demand. In particular, variables such as GDP and car ownership played a key role as drivers in the update of the origin–destination matrices. Finally, the collection of traffic count data allowed the refinement of the estimated demand matrices through a calibration process for road transport.

The second phase consisted in the application of the model through traffic assignment procedures on the updated networks. In order to evaluate the model results, a set of indicators specifically designed for multimodal transport models at the macro scale was selected, based on a review of the existing state of the art. Modal split, connectivity and accessibility were identified as the main dimensions for assessing the performance of the transport system in the Adriatic–Ionian Region.

The analyses conducted on the transport networks of the Adriatic–Ionian Region show that the disparities already observed during the socioeconomic analysis are reflected in the performance of transport infrastructures. Italy clearly emerges as a leading country

within the region, not only from a demographic and economic perspective, but also in terms of network performance. Conversely, the Western Balkans remain relatively underdeveloped, particularly with respect to rail transport. While a significant number of road projects were completed between 2017 and 2023, resulting in a relatively widespread road connectivity, railway infrastructure is still limited, with some areas remaining completely disconnected from the rail network. From an accessibility perspective, this situation translates into a strong dominance of the car mode, which in several areas represents the only available means to access or reach social and employment opportunities.

Based on these findings, the role of institutional frameworks such as EUSAIR and the use of macro-scale transport models appear to be particularly relevant for the evaluation of infrastructure development policies, not only at the national level but, more importantly, at the international and cross-border scale. The results of this study can support policy makers in identifying critical territorial disparities and prioritising investments aimed at improving cross-border connectivity and integration among participating countries. In this sense, the updated EMTM can serve as a valuable analytical tool to support the integration of the Adriatic–Ionian Region within the TEN-T network and to assess the coherence of national infrastructure strategies with supranational objectives.

However, some limitations characterise this type of analysis. Political and economic conditions in several countries make it difficult to focus exclusively on technical and infrastructural aspects. This situation is also reflected in data availability: while data for EU Member States are generally accessible through harmonised sources such as Eurostat, data for candidate countries are often fragmented across national statistical institutes, making the initial data collection and the validation of the model results more complex.

From a modelling perspective, the large geographical extent of the study area inevitably requires some simplifications. In particular, greater emphasis is placed on the modal split sub-model, in order to accurately calibrate the parameters affecting utilities and generalised costs, while generation and attraction processes are treated in a more aggregated manner. Preliminary results therefore require careful interpretation and comparison with previous model versions, in order to identify potential inconsistencies and, where necessary, to apply targeted adjustments to the demand matrices. This is especially relevant for those transport modes and vehicle categories for which reliable and disaggregated input data are difficult to obtain.

Finally, this work represents a fundamental starting point for the development of future transport scenarios within the EUSAIR framework. Building on the updated project lists and on socioeconomic forecasts, the next steps of the modelling activity will focus on the

development of future scenarios with different time horizons. From a demand modelling perspective, this will involve the definition of new updated origin–destination matrices and demand drivers.

In particular, the following scenarios are currently envisaged:

1. for the year 2035, the Baseline Projects' Scenario, including the current rail and road network, ongoing projects and very mature projects whose implementation is already planned and financed
2. for the year 2040, the Long-Term Projects' Scenario, based on the Baseline Projects' scenario and including a selection of additional projects from the programming pipeline, as well as assumptions on further upgrades of existing network sections
3. for the year 2050, the TEN-T Completion Scenario, based on the assumption that the extended TEN-T core network is fully implemented and that its performance targets are achieved.

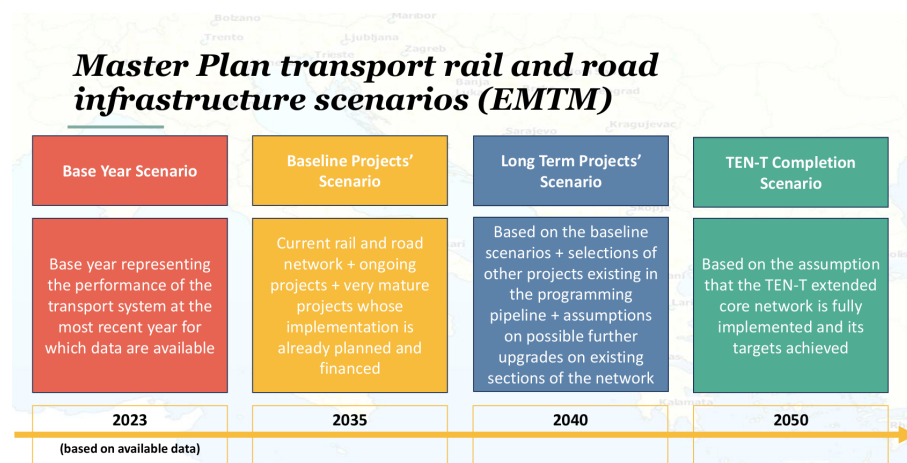


Figure 4.1: Rail and Road Infrastructure Scenarios for the EMTM future development

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