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Strategic multimodal evaluation for air-rail networks

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Abstract

Achieving a modal shift from air to rail is a critical priority for decarbonising Europe's transport sector, requiring models that can capture multimodal passenger behaviour and assess network performance under varying policy and infrastructure scenarios. The Strategic Multimodal Evaluator developed in the MultiModX project, which integrates four core functions: (1) generating possible itineraries across air and rail mobility layers; (2) modelling passenger choice to distribute demand among alternatives; (3) assigning flows to services while respecting capacity constraints; and (4) computing performance indicators to evaluate effectiveness from infrastructure, regional, and passenger perspectives. The methodology is applied to a case study in Spain, examining three policy packages — baseline, multimodal incentivisation (integrated ticketing and CO₂ taxation), and flight bans —revealing limited impact on intra-Spain mobility but demonstrating the model's capacity to capture shifts in travel patterns and infrastructure usage.

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1. Introduction

The topics of multimodality, passenger experience and inclusion, and the development of a European seamless mobility system that meets the goals of the Paris Climate Agreement are gaining traction ([European Commission, 2020](#)). This multimodal vision requires airports to be multimodal nodes of the future, and coordinated planning and collaborative decision-making based on shared information and situational awareness across transport modes as key enablers ([SESAR JU, 2020](#); [ACARE, 2017](#); [European Commission, 2011](#)). Railway planning can help expand airport catchment areas and shift passengers from feeder flights to high-speed rail (HSR) connections, reducing greenhouse gas (GHG) emissions and releasing airport capacity ([Givoni and Banister, 2006](#); [Delgado et al., 2023b](#)). A shift to rail for air connections with suitable HSR alternative, which would require multimodal networks to ensure connectivity, is

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being evaluated in several European countries, with France at the forefront of introducing such a mandate ([Convention Citoyenne pour le Climat, 2021](#)), and Spain considering a similar policy ([PSOE and Sumar, 2023](#)).

The interactions between different transport modes are complex: substitution due to competition; complementarity of services, operating in different regions; and/or supporting each other by covering different segments of a door-to-door journey, as a feeder mode for one another. Therefore, multimodal mobility networks with joint air and rail services are challenging to assess, particularly when focusing on passengers' itineraries ([Delgado et al., 2023a](#)).

In general, a better understanding of the impact of multimodal mechanisms (e.g. integrated ticketing) and incentivisation (e.g. taxation of CO₂ emissions) and enforcement (e.g. flight bans) policies on mobility, from a strategic and door-to-door perspective, is needed.

MultiModX¹, an Exploratory Research Project from the Single European Sky & Air Traffic Management Research (SESAR) programme provides, among other things, Strategic and Tactical Multimodal Evaluators to assess the planned and realised multimodal networks. The Tactical Multimodal Evaluator extends the open-source agent-based model (Mercury), which can simulate and track flights, relevant trains and passengers during a day of operations ([Weiszer et al., 2024](#))². The Strategic Multimodal Evaluator takes advantage of previous research on the graph-based representation of transport networks following the developments of previous projects ([TRANSIT Consortium, 2022](#); [Delgado et al., 2020](#); [Modus Consortium, 2021](#)). This evaluator enables the assessment of air-rail multimodal networks, calculating mobility performance indicators (PIs) that can be extracted at different levels (e.g. region, infrastructure, operator), considering: flight schedules and rail timetables, infrastructure information (connecting times between nodes, region accessibility), policies, and demand. This enables the evaluation of what-if scenarios considering changes in any of these parameters.

This article presents the modelling approach of this Strategic Evaluator, released as open-source³, and applies it to intra-Spain mobility with the evaluation of different policies.

2. Methodology

2.1. Mobility network modelling

The multimodal networks are modelled following the principle of mobility layers connected between them with temporal multiplexes ([Zaoli et al., 2021](#)), as shown in Figure 1. This modelling considers the demand between regions; the characteristics of the infrastructure which enable access to the mobility layers and the transition between them; supply information that enables moving through the layers (i.e., flight schedules and rail timetables); and policies, which impact some of the previous elements.

The starting point is defining *Regions* (R_r), which have demand between them for different passenger archetypes. These archetypes consider the sensitivity of passengers to mobility factors (total travel time, costs and emissions).

$D_a(R_i, R_j)$ represents the demand between region R_i and R_j for archetype a ; $D(R_i, R_j) = \sum_{a=0}^a D_a(R_i, R_j)$ would then be the total between region R_i and region R_j . For example, for the case study of intra-Spain mobility, the regions are defined at NUTS-3 level⁴ (provinces, islands, Ceuta and Melilla) with six passenger archetypes (see Section 3.1).

Each region is connected to one or several infrastructure nodes (airports or rail stations), which can belong to any of the mobility layers. Only two mobility layers are considered in this research (air and rail), but the model allows the definition of as many complementary layers as desired (e.g. additional rail or air layers, or modes, such as bus).

$RA(R_i, N_{lj})$ ($RE(R_i, N_{lj})$) represent the average access (egress) times (door-to-kerb (kerb-to-door)) from region R_i to (from) the infrastructure node (airport or rail station) j of layer l (N_{lj}). These values enable the estimation of the total door-to-door travel time when comparing alternatives. Not all infrastructure nodes are accessible from each region, and more than one node could be accessible from the same region, even if they are located in a different region. Passengers can start and end their journeys at any of the infrastructure nodes accessible from their origin and destination regions.

¹ MultiModX: <https://cordis.europa.eu/project/id/101114815> (Accessed July 2025)

² Mercury – Tactical Evaluator: <https://github.com/UoW-ATM/Mercury> (Accessed July 2025)

³ MultiModX open-source models: <https://github.com/UoW-ATM/MultiModX> (Accessed July 2025)

⁴ Spanish Nomenclature of Territorial Units for Statistics (NUTS) regions (Accessed July 2025):

https://en.wikipedia.org/wiki/NUTS_statistical_regions_of_Spain

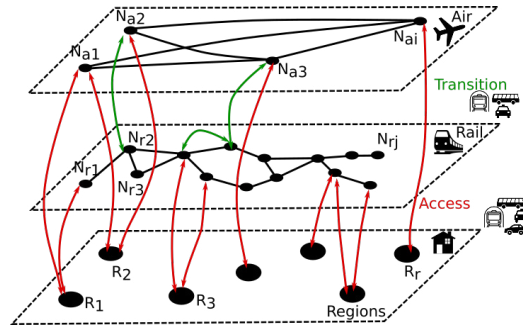


Fig. 1: Multilayer modelling approach

It is possible to transition between mobility layers. $TR(N_{li}, N_{kj})$ represents the required transfer time between two nodes. These could belong to the same mobility layer (for example to allow transfers between two train stations within the same city using the metro network), or enable multimodal connections between layers. Each node that allows intra-mode transfers has a minimum connecting time defined ($MCT(N_{li})$). This is the minimum time required to change between flights at an airport or between trains at a given rail station.

Some additional processes are considered within the infrastructure nodes: $KS(N_{li})$ represents the time required to reach the service (flight/train) from the kerb of the infrastructure (airport/rail station). This includes processes such as check-in or security. $SK(N_{li})$ represents the time required by the passenger to reach the kerb from the moment the service arrives at the node (i.e., the flight arrives at the gate or the train to the rail station).

Flights and trains define the connectivity within the air and rail mobility layers, respectively. The model transforms the individual connections provided by these into *services*. A service (S_i) is defined as a temporal link between two nodes in the same mobility layer. For flights, this is a natural association; train trips (from General Transit Feed Specification (GTFS)) are transformed into individual services between the different stops served. For each service, the model defines:

- Departure and arrival times in UTC ($SOBT(S_i)$ and $SIBT(S_i)$);
- Departure and arrival nodes ($FROM(S_i)$ and $TO(S_i)$), i.e., airports (N_{aj}) and rail stations (N_{rk});
- Other parameters: mode type (air, rail) ($M(S_i)$); operator (or alliance) ($OP(S_i)$); capacity ($CAP(S_i)$); cost ($C(S_i)$); and emissions per passenger ($CO2(S_i)$), provided or estimated by the model (Montlaur et al., 2021).

Intralayer connectivity between two services (S_i and S_j) is possible if the subsequent service departs from the same node as the previous one ($TO(S_i) = FROM(S_j)$), they their operator (or alliance) is the same ($OP(S_i) = OP(S_j)$), and the MCT is respected ($SOBT(S_j) \geq SIBT(S_i) + MCT(FROM(S_j))$).

Finally, multilayer connections between two services (S_i and S_j) are valid as long as a transition exists between the arrival node of the first service and the departure node of the second one, and the connecting times are respected: $TR(TO(S_i), FROM(S_j)) \geq 0$ and $SOBT(S_j) \geq SIBT(S_i) + SK(TO(S_i)) + TR(TO(S_i), FROM(S_j)) + KS(FROM(S_j))$.

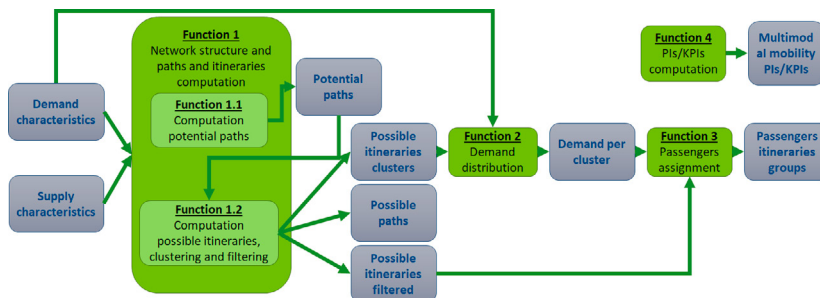


Fig. 2: Functional flow chart of the Strategic Multimodal Evaluator

2.2. Functional overview

As shown in Figure 2, the computation flow is organised into four consecutive functionalities. Function 1 creates the previously described mobility network (see Section 2.1 and Figure 1) and applies two high-level subfunctionalities. First, to find potential and possible paths between regions. Then, the n -fastest possible itineraries, considering service schedules and respecting MCTs are computed. Each itinerary I_i is defined as a sequence of services $I_i = [S_1, S_2, \dots, S_n]$, and for a given origin region R_o and destination region R_d , the list of possible itineraries is denoted by $PI_{od} = [I_1, I_2, \dots, I_k]$.

For each itinerary $I_i \in PI_{od}$, performance indicators relevant to passenger preferences are computed as follows:

- Total travel time: $TTT_i = AT_i - DT_i$, with $DT_i = \text{SOBT}(S_1) - \text{KS}(\text{FROM}(S_1)) - \text{RA}(R_o, \text{FROM}(S_1))$ and $AT_i = \text{SIBT}(S_n) + \text{SK}(S_n) + \text{RE}(R_d, \text{TO}(S_n))$, where S_1 and S_n are the first and last services in I_i .
- Total CO₂ emissions: $TCO2_i = \sum_{j=1}^n \text{CO2}(S_j)$
- Total cost: $TC_i = \sum_{j=1}^n \text{C}(S_j)$
- Number of connections: $NC_i = n - 1$
- Mode type M_i , defined as: $M_i = \text{air}$ if $M(S_j) = \text{air}$ for all $S_j \in I_i$; $M_i = \text{rail}$ if $M(S_j) = \text{rail}$ for all $S_j \in I_i$; and $M_i = \text{multimodal}$ otherwise.

The itineraries are grouped into clusters of equivalent alternatives from the passenger's perspective, based on these performance indicators. Given an origin region R_o and destination region R_d , the list of alternative clusters is denoted by $A_{od} = [C_1, C_2, \dots, C_m]$, where each cluster contains itineraries with similar characteristics. The average performance of each cluster is calculated (average total travel time, CO₂ and cost) and used to retain only Pareto-equivalent clusters, allowing for some margins per indicator, reducing the number of alternatives in A_{od} .

The assignment of passengers to individual services (i.e., itineraries) is conducted in two steps: the distribution of demand to itineraries' clusters, performed by Function 2, and the assignment of demand to the itineraries within the clusters, performed by Function 3.

Using a previously calibrated logit model (see Section 4.1 for details on this calibration), the demand between regions ($D(R_o, R_d)$) is distributed among the different clusters available between those regions (A_{od}).

The logit model computes a utility function for each passenger archetype (a) and cluster (C_i) (Equation 1):

$$u_a[i] = \alpha_{a_train} \cdot \text{train}_i + \alpha_{a_flight} \cdot \text{flight}_i + \alpha_{a_multimodal} \cdot \text{multimodal}_i + \beta_{a_time} \cdot \text{travel_time}_i + \beta_{a_cost} \cdot \text{cost}_i + \beta_{a_co2} \cdot \text{CO2}_i \quad (1)$$

where: train_i , flight_i and multimodal_i are binary variables (1 or 0) describing M_i of the itineraries in cluster C_i , and travel_time_i , cost_i and CO2_i are the average total door-to-door travel time, cost (Euros) and CO₂ emissions (kg) for the itineraries in C_i . The sensitivities of the passenger archetype a to the modes of transport used are captured by α_{a_train} , α_{a_flight} , and $\alpha_{a_multimodal}$; and β_{a_time} , β_{a_cost} , and β_{a_co2} are the sensitivities to the total travel time, cost and CO₂ emissions respectively. The logit model, therefore, has different sensitivities depending on the passenger archetypes.

The utility of each alternative for each passenger archetype is translated into probabilities with Equation 2. The probability of archetype a to select the cluster (C_i) for a given OD pair depends on the utility of that alternative ($u_a[i]$) and the utility of all n alternatives available between the OD pair.

$$P_a[i] = e^{u_a[i]} / \sum_{j=1}^n e^{u_a[j]} \quad (2)$$

Finally, the demand is distributed among the alternatives based on these probabilities, creating a *flow* of passengers which describes their preference. The attractiveness of the alternatives can be increased or reduced as a function of policies (e.g. introducing integrated ticketing or with a CO₂ tax).

To finalise the network loading, the next step (Function 3) is the assignment of passengers to individual options within each cluster, i.e., to the individual services (flights and trains), while considering their capacity ($\text{CAP}(\text{TRIP}(S_i))$). This is computed with a lexicographic optimisation framework with integer programming with

three objectives: maximising the total number of connecting passengers, then the overall number of passengers assigned, and finally minimising underutilisation. This ensures that passengers with multiple legs can use the system's capacity and that passengers are distributed among different services, avoiding bunching of passengers in services.

The outcome of the Strategic Multimodal Evaluator is the individual passengers' itineraries, the desired demand (passenger flows), and the possible itineraries between regions. These datasets can then be processed (by Function 4) to compute mobility indicators such as total travel time, modal share, CO₂ emissions. Different variants of the indicators can be computed. For example, focusing on average or percentiles, aggregated for the whole network or considering only specific origin-destination pairs or infrastructure nodes.

3. Case studies

3.1. Scope: Demand, Supply and Infrastructure

The results presented in this article focus on intra-Spain mobility with demand flows between the 49 biggest cities. Bueno-González et al. (2024) analysed anonymised mobile phone network data (MND) for a year of mobility within Spain, inferring six passenger archetypes and estimating the demand between all NUTS-3 regions in Spain for a *nominal* busy 2019 (pre-COVID) day per archetype. Flight schedules are obtained from OAG for the 6th September 2019, which has been selected as a *nominal* busy day of aviation pre-COVID. Due to the recent increment in rail operations, rail timetables, provided by the International Union of Railways (UIC), are from a busy and *nominal* day from 2023 (20th September 2023), only rail stations that provide connectivity between NUTS-3s are considered.

Based on EUROSTAT census data, the centroid of the population of each NUTS is computed and used to estimate the access and egress time to the transportation nodes of the network. The accessibility of nodes from the NUTS is based on MND. MCTs for rail stations are provided by UIC, and for airports, these are based on historical datasets. The intra-layer connectivity considers times observed in mobility applications. Finally, processing times (KS and SK) are defined based on expert judgment.

3.2. Scenarios

Table 1 describes three policy packages used to create the scenarios. These combine three policies: Integrated ticketing to support multimodality (reducing multimodal connecting times by 30 and 15 minutes for rail-to-air and air-to-rail connections); Additional CO₂ taxation of 0.15€/Kg CO₂ for flight emissions; and Flight-ban eliminating flights when a high-speed rail (HSR) alternative of up to 3h is available.

Table 1: Policy packages to create scenarios.

Policy package	Integrated ticketing	Additional CO ₂ taxation	Flight-ban
PP00 – Baseline	Not available	Not additional CO ₂ taxation	No flight-ban
PP10 – Multimodality incentivised	Integrated ticketing	Additional CO ₂ taxation	No flight-ban
PP20 – Multimodality enforced	Integrated ticketing	Additional CO ₂ taxation	Flight-ban

4. Results

4.1. Calibration and validation

The logit model is the core of the Strategic Multimodal Evaluator as it captures the preference of passengers to select alternatives. Six models are independently calibrated, one per passenger archetype, by mapping historical MND to the computed possible itineraries of the baseline scenario. The results of the calibration show that most archetypes prefer flights to multimodal alternatives and flights over train journeys. All archetypes present a statistically significant negative correlation with respect to CO₂ and time.

In addition to calibrating the model with historical data, a comparison was conducted between MND and the Strategic Multimodal Evaluator's output for selected origin-destination pairs. The results are generally adequate, as in the Barcelona–Madrid case, where the assignment of the logit model closely matches the observed data (76.6% to HSR, 23.2% to flights, and 0.2% to regional trains). Other pairs highlight some of the model limitations, such as a slight overestimation of the preference to use infrastructure located outside the origin/destination NUTS, as the model lacks cost and emissions for access/egress, or difficulties in differentiating between nodes within the same NUTS.

4.2. Comparison of scenarios

4.2.1. Demand satisfied and mode usage

In the baseline scenario (PP00), 389K passengers are assigned to services (80.9% of the original demand of 481K passengers), with an average load factor of 69.8% and 69.5% for rail and flight services, respectively. Most trips are rail itineraries (72.1%), 26.3% are flights, and only 1.6% (6.4K passengers) are multimodal. This is expected, as the scope is limited to intra-Spain mobility. Madrid, Valencia and Barcelona airports are used for most multimodal journeys, which tend to start or end in peripheral regions and include flights to the islands. In the incentivised case (PP10), similar results are observed, with a slight increase in multimodal journeys (2.0%) and in rail load factor (70.1%).

The enforced case (PP20) with the flight ban removes 104 out of 1,253 flights; mainly affecting flights between Madrid (LEMD) and Malaga (LEMG), Alicante (LEAL), Barcelona (LEBL), Pamplona (LEPP), Seville (LEZL), Valencia (LEVC). In this case, there is a small reduction in air share (23.8%), and a slight increase in multimodal journeys (2.1%), but mainly an increase in rail trips (74.1%). This is reflected in a higher load factor for rail (71.3%). In some corridors, the capacity is fully utilised, as in the Barcelona-Madrid case, where only 3.9K passengers are assigned in PP20 from close to 6K passengers in PP00 and PP10. This leads to a slightly smaller demand assigned: 381K passengers (79.2% of the total demand).

If we focus on region-pairs that in PP00 use any of the 104 banned flights in PP20, we can see that in PP00 between those regions, the mode share was 18.1%, 80.7%, and 1.2% for air, rail and multimodal, respectively; while in PP20 we observe 7.8%, 90.6% and 1.5%. So, passengers are mostly shifted to rail instead of multimodal journeys. A reduction of capacity leads to fewer demand being served: from 94.5K passengers in PP00 to 86.6K passengers in PP20.

4.2.2. Travel patterns and infrastructure

The volume of passengers directly affected by the flight ban is low: only 104 flights with a rail alternative are removed, and as only intra-Spain mobility is considered, those passengers have, by construction, a direct rail alternative. However, some origin-destination pairs generate new travel patterns even if they are not directly impacted by it.

Examples of these newly formed paths are observed in the routes between Valencia and Barcelona to Madrid. With the flight ban, the direct flight to Madrid is no longer possible, but an alternative of connecting in Palma de Mallorca (LEPA) or Ibiza (LEIB) to then fly to Madrid (LEMD) appears. Only 5 passengers (0.2% of the assigned demand) decide to fly from Valencia (LEVC) to Madrid (LEMD) via Mallorca (LEPA); and 152 passengers (3.9% of the assigned demand) decide to use the route Barcelona (LEBL) – Ibiza (LEIB) – Madrid (LEMD). In both cases, it is a minority, as the rail option remains the most suitable (96.1% of the passengers between Barcelona and Madrid use HSR). However, it is interesting to see this pattern, as overall there is a lack of capacity in the rail system (1.9K fewer passengers are served between Barcelona and Madrid in the P20 scenario with respect to the baseline).

This effect results in some airports not being affected by the flight ban, increasing their relevance as connectivity nodes. In particular, the airports of the Balearic Islands increase the number of connecting passengers from 93 to 190 for Palma de Mallorca (LEPA), from 22 to 546 for Ibiza (LEIB) and from 0 to 28 for Menorca (LEMH).

Some regional airports also gain relevance as part of multimodal journeys due to the flight ban. Without the ban, larger airports, which are also located in cities with better rail links, were capturing the demand; but with the flight ban, alternatives that were less appealing are used, and regional airports can provide connectivity to adjacent regions. Valladolid (LEVD) is an example of this: with the flight ban, it experiences a surge in the number of multimodal journeys using the infrastructure (166.1% higher than in PP00 and a 105.4% increase with respect to PP10), as shown in Table 2. In absolute value, the number of multimodal passengers is still small, but it is worth noticing that there are only 2 arrivals and 2 departures for LEVD in the day. This means that of a combined 369 seats arriving at LEVD, 202 (54.7%) continue their journey multimodally, and 104 (28.2% of the flight seating capacity) arrive at the airport as part of a multimodal journey in the PP20 scenario.

Table 2: Number of passengers with multimodal journeys from/to the airports for the different scenarios. (% Variation with respect baseline)

Airport	Scenario	Onward multimodal journey	From multimodal journey	Total
Madrid (LEMD)	PP00 – Baseline	1,735	1,658	3,393
	PP10 – Incentivised	2,015 (16.1%)	2,315 (39.6%)	4,330 (27.6%)
	PP20 – Enforced	1,872 (7.9%)	2,035 (22.7%)	3,907 (15.1%)
Valladolid (LEVD)	PP00 – Baseline	78	37	115
	PP10 – Incentivised	95 (21.8%)	54 (45.9%)	149 (29.6%)
	PP20 – Enforced	202 (159%)	104 (181.1%)	306 (166.1%)

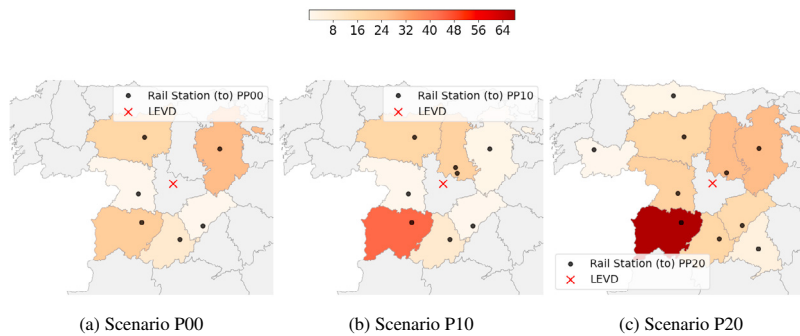


Fig. 3: Final regions for multimodal journeys flying to Valladolid (LEVD) and continuing by rail for the three scenarios.

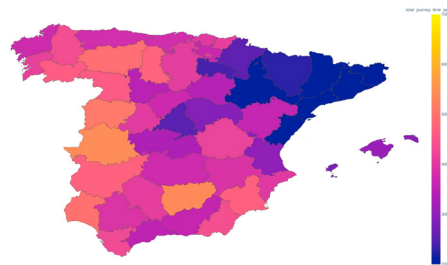
Fig. 4: Average travel time from Catalonia (ES51) to other regions in Spain in the *baseline* scenario (PP00).

Table 2 also provides the number of multimodal connecting passengers at Madrid airport (LEMD). As shown, when the incentivised policies are in place (PP10), both airports increase the number of multimodal passengers similarly: 27.6% increase for LEMD and 29.6% for LEVD. In contrast, for Madrid, when the flight ban is implemented, the number of multimodal passengers is reduced with respect to the incentivised case (from 4,330 to 3,907 passengers). This could be expected as international connections are not considered, and flights to main destinations within Spain are banned, impacting the feeding of the hub with rail to these destinations. Those intra-Spain flows are rerouted to other alternatives.

Figure 3 shows for LEVD the rail stations used as a continuation of a multimodal journey for the three scenarios. As depicted, when multimodality is incentivised (PP10) and the flight ban is applied (PP20), the number of regions (and passengers) that use LEVD as their local regional connector increases.

4.2.3. Travel time and regions connectivity

The final example of results that can be obtained with the Strategic Multimodal Evaluator is the estimation of travel times and the connectivity of the regions. Figure 4 shows the average travel time (door-to-door) from the Catalonia

region (North-East Spain) (NUTS-2 ES51) to the rest of the regions in Spain (Canary Islands not shown). This is calculated by averaging the travel time from the four NUTS-3 areas which compose ES51. As shown, it is easy to identify the regions that are part of the HSR line, the connectivity with Madrid (by direct HSR services) and regions well connected by air services such as the Balearic Islands.

5. Conclusions and future work

This article presents a methodology for modelling strategic multimodal air-rail networks to evaluate passenger-centric mobility indicators and policy impacts on door-to-door journeys. The models, released as open-source, support scenario-based analysis of policies of integrated ticketing, CO₂ taxation, and flight bans. Applied to intra-Spain mobility, results show multimodal travel remains limited (around 2% of trips) even with interventions, due to the strong connectivity of Spain's high-speed rail network. With international connections, the role of hubs like Madrid and the share of multimodal trips are expected to grow. Short-haul flight bans shift demand toward rail, but capacity limitations restrict satisfaction of passenger preferences, reducing fulfilled demand to 79.2%.

The model captures path and infrastructure changes, such as increased roles for regional and peripheral airports (such as Valladolid and the Balearic Islands). Future work should improve access/egress cost and emissions modelling and better handle demand-capacity mismatches, possibly through iterative assignment. Including international connections is key to fully assessing the broader policy impacts on mobility and infrastructure use.

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