Challenges of multimodal door-to-door mobility modelling

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***Abstract*—Air-rail multimodal mobility has the potential to play a significant role in addressing European mobility challenges such as emissions reduction goals, and capacity shortages, and in moving towards a wider European multimodal transport network. There is still a need to better understand the potential role of rail when substituting current air links both from a strategic and a full, tactical mobility perspective, particularly when passenger connections are considered. In line with these challenges, this paper presents some of the work conducted in the Modus project (H2020-SESAR) and develops an innovative approach towards data driven, integrated air-rail modelling, considering passenger door-to-door itineraries.**

***Keywords*—Multimodal mobility; Integrated modelling; Air-rail networks; Door-to-door transport**

I. Introduction

The topics of multimodality, passenger experience and inclusion, as well as creating a seamless mobility system within Europe that meets the goals of the Paris Climate Agreement, are high on the agenda of shaping the future European transport system. Different mobility and aviation strategies outline respective objectives accordingly. The Sustainable and Smart Mobility Strategy in 2020 highlights the need for sustainable mobility within a fully integrated network, including widespread high-speed rail (HSR) connections on short-haul routes as a complement for long-haul air transport coverage [1]. Furthermore, the establishment of multimodal mobility requires the efficient allocation of capacity, the accessibility of all regions for all passengers, and aligned passenger rights, as well as multimodal information and ticketing. In line with this, airports are considered to be multimodal nodes of the future [2]–[4]. Important requirements for seamless, multimodal travel are multimodal regulatory and legal frameworks as well as the exchange of travel and passenger itinerary information in a privacy-preserving context.

A particular role in realising a multimodal European network, as well as addressing emission reduction goals and capacity shortages, among others, is addressed by joint air-rail mobility. In terms of collaboration and cooperation, a recent example of (enhanced) interline or codeshare agreements is Deutsche Bahn in Germany becoming the first intermodal partner of the Star Alliance [5], offering seamless and single ticketing options for passengers on air-rail journeys. Recent discussions and developments in the air-rail context also focused on the replacement of short-haul air routes by high-speed rail, where applicable. Inducing, or even mandating, a shift from air to rail on routes with feasible high-speed rail replacement options has been evaluated across several European countries, with France being on the forefront of introducing this [6], [7]. Initially, a ban of flights which could be replaced by an up to four-hour rail connection was envisaged. Later, the French national assembly decided to change this requirement to two and a half hours.

The interaction between different transport modes is manifold. It can be in the form of substitution, for example, by competing for the best service to travellers, or as complementary services by covering different segments of a door-to-door (D2D) journey and serving as feeder mode to one another. There is still a need to better understand the potential role of rail when substituting current air links both from a strategic and a full mobility perspective. This paper presents some of the work conducted in Modus Research and Innovation action from the SESAR Horizon 2020 programme[1]. Modus aims at modelling future scenarios were multimodality is present considering the passengers' full D2D mobility. This paper focuses on highlighting some of the challenges of modelling these multimodal scenarios (experiments), describing the novel approach adopted. Through the first results, it also sets out to explore the impacts of various future scenarios, such as a short-haul ban in four European states with a corresponding shift to rail, where available, on various key performance indicators, such as D2D travel times and CO_2 per passenger.

II. Air-Rail Substitution and Complementary Analysis

The substitution potential of air and rail applying modal choice analysis has been the subject of various studies. Travel time and frequency are some of the most important factors in terms of modal travel behaviour [8], [9]. The analysis of 4815 routes within the scope of the Modus project has analysed fare-demand elasticities in France, Germany and Spain [9]. Furthermore, the analysis of the effects of the introduction or presence of a high-speed rail connection on air transport services shows a reduction in offered air transport seats, fares or overall services on these particular routes [10]–[12].

[1]https://modus-project.eu/ (Accessed October 2022)

In addition to factors driving multimodal travel behaviour, different studies have been investigating and comparing the environmental impact of different transport modes across various distance segments. The European Environment Agency conducted a well-to-wheel/wake analysis and calculated emission costs for different aircraft types and high-speed rail [13]. Assuming certain occupancy rates of these two modes, and introducing uncertainty for the non-CO_2 effects of air transport, the emission costs for air transport are higher than those for rail, for distance segments of 500 and 1000 km. Similar results are found in [14] where emissions per passenger-km are considered. Transport&Environment find that the CO_2 emissions from aviation in Europe could potentially be reduced between 2% and 4% for flights up to 1000 km [15]. Oxera investigates short-haul of flights up to 500 km and potential emissions savings of 1% to 2% [16]. Avogadro et al. find a similar range of emission reduction potential (4.7%) by analysing route substitutability between air and rail in Europe [17].

In addition to price, frequency and environmental impact of different transport modes, door-to-door travel time plays a significant role in passengers' decision making. The current and future availability of air and rail infrastructure and respective connection times are a decisive factor in this regard. For 51 of the 150 flight routes with the highest passenger numbers in Europe, as highlighted by Greenpeace [18], a rail alternative within six hours is available. Considering intra-European routes, [17] find a potential replacement of 7.2% of flight seats with feasible rail alternatives and a related maximum 20% increase in travel time . In [14], door-to-door travelling times were estimated to be equivalent up to 600 km when high-speed rail is available. The French national assembly ban on some domestic flight routes is framed in this context [6], [7]. Previous research indicates that this approach can lead to significant emission reductions [19], [20] even if the infrastructure needs to be deployed [21].

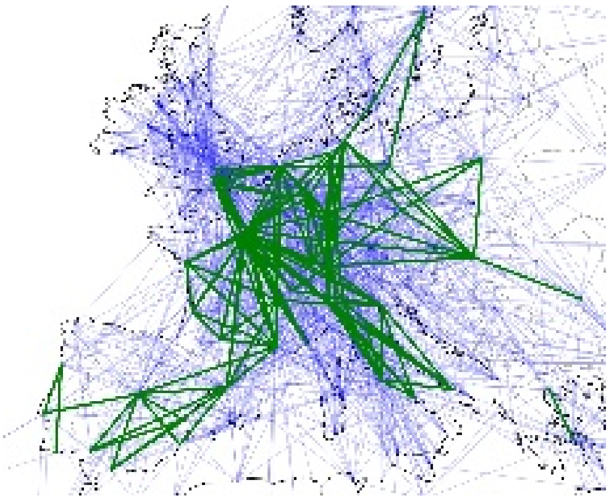

Figure 1. Rail and air network considered

A first network analysis was carried out in Modus to assess the maximum potential air replacement that can be achieved with the fast rail network in Europe. Figure 1 presents the flights with a distance lower or equal to 1100 km operating in Europe with an overlap of the rail network, which could potentially be used to replace them. One of the challenges of replacing flights by rail is the impact of these replacements in passenger connectivity at hubs. Therefore, in this analysis data from a busy day in 2014 schedules and passenger itineraries are considered as modelled in the previous H2020-SESAR research project Domino [22]. Rail alternatives are extracted considering 2019 routes from the MERITS database [23].

The analysis conducted assesses the impact of a flight ban, where a rail alternative is possible. Figure 2 presents the results obtained with the network previously described as a function of the length of the flight ban up to 1200 km.

First, is it worth observing that the flights of up to 1200 km represent almost 60% of all the schedules considered (almost 16 000 flights). From these, if the ban were to be introduced, fewer than 2000 flights would be affected, *i.e.*, around 12% of flights. As shown in the graph, a ban of 1100 km would impact 1942 flights (12.9%). This would represent the use of 288 rail links (origin-destinations). It is interesting to observe how, as the ban distance increases, the number of flights impacted increases too, but from around 800 km the marginal gain diminishes significantly. At 800 km, 15.1% of the flights can be replaced (1800 flights) using already 256 rail links (only 32 fewer rail connections than with a 1100 km ban).

An interesting addition to the analysis is the consideration of passenger itineraries, including their connections at hubs. As shown in Figure 2, the number of connecting passengers with respect to non-connecting ones that are replaced by rail as a function of distance decreases (from 29.7% of the passengers at 300 km, to 20.0% at 1100 km). However, even if the total number of connecting passengers is low, they have a significant impact on the number of flights which have at least a connecting passenger on them and that is replaced by rail. For example, at 800 km a total of 1800 flights can be replaced by rail, but from these more than 1500 have some passengers with connections. In summary, policies such as the flight ban introduced in France might have very limited impact if limited to flights without connections, as short flights tend to include many feeders to the hub with connecting passengers. Connecting passengers are therefore not too significant in volume (around 20-25% of passengers being potentially moved to rail), but present a significant challenge for the replacement of air by rail. Multimodal itineraries are therefore a must when these substitution policies are considered. The use of rail for multimodal passenger itineraries presents a set of challenges when considering door-to-door mobility: dedicated models are therefore required.

III. Multimodal Scenarios

A multitude of high-level European mobility strategic agendas have been consulted, and aspects relating to connectivity, environmental impact, the integration of additional demand and technological innovation and its widespread implementation have been identified, to have a significant impact on

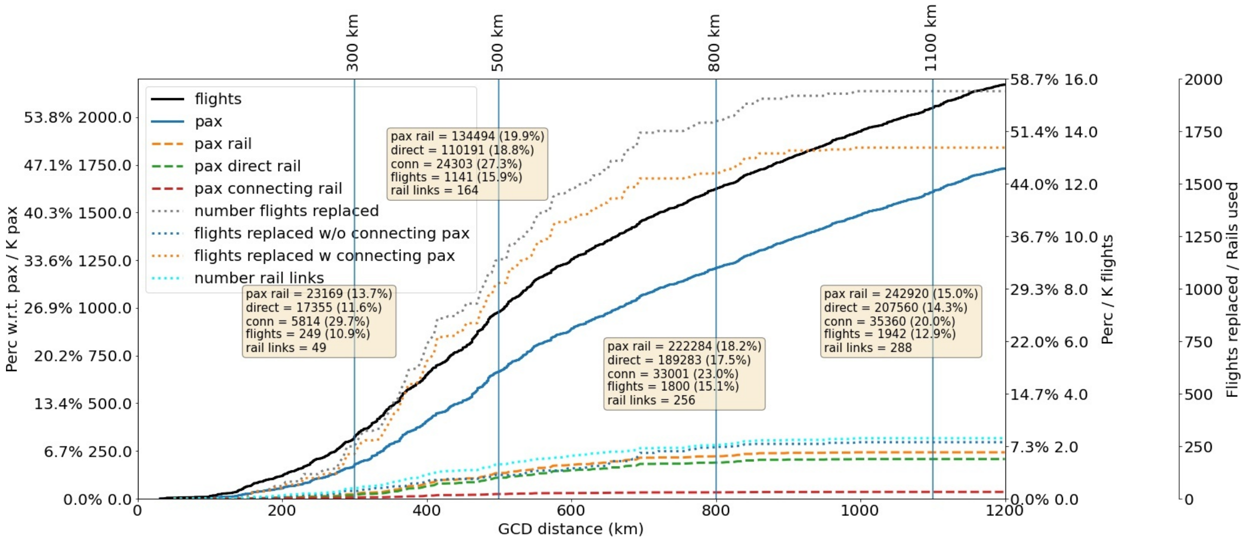

Figure 2. Rail and air network considered

the future development of multimodal mobility scenarios in Europe. Each scenario is described by a range of parameters which vary across the four possible development paths [24]. Socio-economic, environmental, political, and network developments are depicted by factors such as population, gross domestic product, or air and rail traffic demand. Transport supply and technological development are described by air and rail transport frequency, travel time, price indices for the two transport modes, or the degree of implementation of new technologies.

TABLE I. SCENARIOS DESCRIPTION

Scenario 1 – ‘Pre-pandemic recovery’ (baseline scenario)
The European transport market recovers to pre-crisis levels; air transport and railway network structure remain similar to today’s. The implementation of innovative technologies as well as market-based measures facilitate the reduction of emissions in the transport sector. This scenario serves as the baseline for the comparison with different future development paths.
Scenario 2 – ‘European short-haul shift’
High share of short-haul air traffic is replaced by a cooperation between rail and air; reduction in overall air traffic on short-haul routes in Europe. High quality transport network with high-speed rail services on short-haul distances is established, clean aviation services improving the coverage of long-haul routes. Increased level of cooperation between air and rail to provide both door-to-door solutions as well as efficient connectivity of European regions.
Scenario 3 – ‘Growth with strong technological support’
High growth rates of the transport sector until 2040, significantly exceeds that in the baseline scenario. Emphasis on uptake of technological innovations to both reduce emissions and alleviate capacity shortages, widespread implementation of respective innovative technologies in the air transport sector.
Scenario 4 – ‘Decentralised, remote and digital mobility’
Population becomes more dispersed across rural and remote regions; with these becoming much more attractive due to increased options for remote working and virtual meetings.

Table I outlines future scenarios variously considered in Modus to compare their respective impact outcomes. These are numbered 1-4. Table II further details these as experiments for the modelling, using the same scenario numbers (1-3; scenario 4 is not simulated at this stage of Modus). (1) serves as the current baseline and depicts the 2019 air and rail traffic situation. The current baseline is then extrapolated into a future baseline (2a), and a short-haul ban is further introduced as (2b). The scenario with strong growth enabled by technological innovation is run as experiment 3a. The various air traffic growth rates are described further in Section IV. The tactical disruption analogue experiments are indicated ‘$*$’ (*e.g.* (1^*) and are explained in Section IV-F.

IV. MULTIMODAL PASSENGER MOBILITY MODELLING

Turning to the modelling of gate-to-gate flight and passenger itineraries, considering different mobility phases (strategic, pre-tactical and tactical), such models have been developed in previous research [30]. The tactical mobility model, ‘Mercury’, focuses on the gate-to-gate (G2G) phase of the passenger itineraries. In Modus, the model has been expanded to consider multimodal journeys. The modelling approach for the multimodal door-to-door mobility model is the decomposition of the total travel into different stages as presented in Table III.

A multimodal journey is exemplified when a passenger takes a plane and then a train from the city centre to get to their destination, the journey would then be composed of: door-to-kerb, kerb-to-gate, gate-to-gate, gate-to-kerb, kerb-to-platform, platform-to-platform, platform-to-door.

Figure 3 presents the different processes and data flows required to generate the input of the mobility model (with pre-computation of passenger itineraries, flight schedules, flight plans and rail alternatives) and post-processing of the first-last mile travel. The approach described covers all three phases of transport: with a strategic layer generating demand and supply flows and rail alternatives, a pre-tactical layer which translates those flows into individual schedules and passenger itineraries, and the tactical execution of the itineraries in the tactical layer.

TABLE II. EXPERIMENTS CONDUCTED

Experiment	Air layer	Rail layer	Environmental assumptions
1. Current baseline	Air traffic and passenger itineraries for 2019	Rail traffic 2019	Current aircraft emissions, from BADA† For rail 33 g CO_2 / pax km for all trains‡
2a. Future baseline	Air traffic and passenger itineraries for 2040 regulated growth⋆	Rail infrastructure and traffic for 2040	Future aircraft emissions: 7.5% reduction⊤ For rail 26 g CO_2 / pax km (year: 2030) for all trains
2b. 2a with short-haul ban	Air traffic and passenger itineraries for 2040 regulated growth, removing flights less than 500 km in France, Germany, Italy and Spain	Rail infrastructure and traffic for 2040	Future aircraft emissions: 7.5% reduction⊤ For rail 26 g CO_2 / pax km (year: 2030) for all trains
3a. Future high growth (with technology)	Air traffic and passenger itineraries for 2040 global growth	Rail infrastructure and traffic for 2040	Future aircraft emissions: 7.5% reduction⊤ For rail 26 g CO_2 / pax km (year: 2030) for all trains

† BADA stands for Base of aircraft data and contains aircraft performance data enabling different assessments, environmental included. [25]
‡ Current [26] and future values [27]
⋆ The air traffic and passenger demand are grown based on the Regulation and Growth and Global Growth forecasts from EUROCONTROL's Challenges of Growth forecast. [28]
⊤ According to the European ATM Master Plan, it is expected the aircraft emissions will reduce between 5-10%. We chose 7.5%. [29]

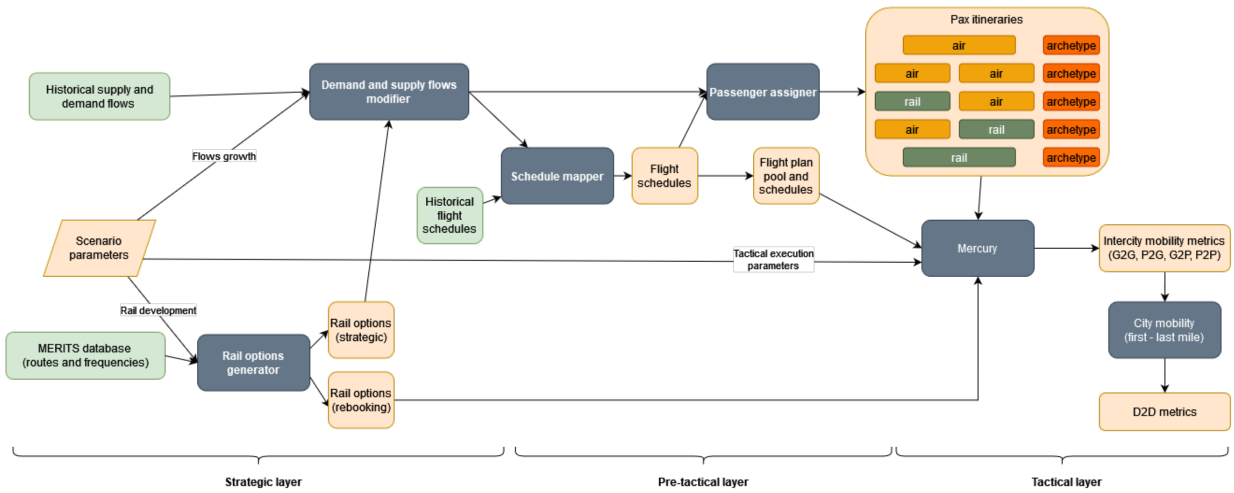

Figure 3. Passenger mobility model implementation

Through the demand and supply flow modifier component the current supply of seats (*i.e.*, flows) and passenger demand are grown to the future values and split between air-only, multimodal and rail itineraries. The outcome of this process is then used by the schedule mapper (based on historical schedules) to produce future schedules. Note that we need to ensure that possible flight plans are available for each schedule suggested. Then the demand flows are translated into individual passenger itineraries by the passenger assigner considering the available schedules. The outcome of this process is a set of passenger itineraries (indicating which flights and/or rail are used) along with their passenger archetype (see next section). The Mercury model simulates the mobility of the passengers in the rail and air network, for specific city archetypes (see next section). For experiments where severe disruptions are modelled in Paris and Madrid, rail is used as a substitution. The city mobility (first-last mile) model incorporates the travel times required to access the travel infrastructure (airport or rail station). Model components are explained in corresponding sub-sections.

A. *City (and passenger) archetypes*

The holistic approach in Modus, integrating air and rail in the wider, door-to-door context, prompted the development of *city* archetypes, rather than focusing on airports or railway stations *per se*. A city archetype denotes a specific combination of airport and railway connections and allowed us to generalise the modelling based on the construction of typical urban travel infrastructure. This impacts the modelling at two levels. Firstly, it allows, holistically, the consideration of movements between 'Paris' and 'London' and the future of such flows, rather than being tied to specific constraints at particular airports, for example. Secondly, it allows the construction of urban mobility models relating, for example, to airport and railway station access and egress, with generic travel time distributions per archetype, drawing both on models of public transport data and a previous framework developed in the DATASET2050 project [31]. This further work has been presented elsewhere [32], whereby actual European city data were used to build the models. The higher-level, generic formulation across five

TABLE III. Air, rail and multimodal trip segments

Door-to-door flight segment	
Door-to-kerb (D2K)	Time necessary to get from home location to entrance of the airport.
Kerb-to-gate (K2G)	Time necessary to go through all departure airport processes and reach gate.
Gate-to-gate (G2G)	Time necessary for flight to arrive at destination.
Gate-to-kerb (G2K)	Time necessary to go through all arrival airport processes and reach entrance.
Kerb-to-door	Time necessary to get from entrance of airport to final location
Door-to-door rail segment	
Door-to-platform	Time necessary to get from home location to rail station platform.
Platform-to-platform	Time necessary for train to arrive at destination.
Platform-to-door	Time necessary to get from rail station platform to final location.
Multimodal segments	
Gate-to-platform (G2P)	If rail station is located at airport and onward segment of trip is by rail.
Platform-to-gate (P2G)	If rail station is located at airport and prior flight segment of trip is by rail.
Kerb-to-platform (K2P)	If rail station is not at airport, *e.g.* at city centre, and onward segment of trip is by rail.
Platform-to-kerb (P2K)	If rail station is not at airport, *e.g.* at city centre, and prior flight segment of trip is by air.

city archetypes is shown in Table IV. In total, 176 European airports underpin the framework.

TABLE IV. Classification of city archetypes

City archetype	Airport archetype	Railway connection to airport	Further railway info (if applicable)
1	Main hub	Good inter-regional, direct HSR to airport	-
2	Main hub	Good inter-regional, no direct HSR to airport	HSR connected to the city only
3	Secondary hub	Good inter-regional, no direct HSR to airport	HSR connected to the region only and/or good main line rail.
4	Large/ medium	Good inter-regional, no direct HSR to airport	
5	National/ regional	Near good inter-regional/ No HSR	

In matching airports to an appropriate city archetype level it is important to differentiate between airports which have good HSR / mainline / inter-regional rail and those which do not. Under different future scenarios, the model also allows for the 'promotion' of lower to higher archetypes, based on the anticipated provision and expansion of rail services in Europe. (This draws on rail industry data collected from multiple sources, combined with expert inputs, and develops the work reported in Section IV-E, but is not reported further here.)

Complementarily, and analogously, to the city archetypes, different passenger profiles characterising distinct travel behaviours have been applied, as reported in [33]. These *passenger* archetypes, in combination with the city archetypes, define the appropriate parameterisation of the urban access/egress and urban mobility models, obviating the need to model either individual cities or passengers, whilst appropriately capturing the heterogeneity thereof.

B. Demand and supply flows modifier

The demand and supply flows modifier component lies in the strategic layer, its role being to produce the future flows, which represent the future supply of seats and demand in an aggregated volume of passengers. The generated supply and demand volumes are varied across the scenarios (experiments) presented in Section III. In order to prepare the future supply and passenger demand flows, we start from the historical (2014) flows produced in the Vista project [30]. Those flows are then increased using EUROCONTROL's Challenges of Growth (2018) forecasts [28], more specifically using the traffic multipliers related to the appropriate forecast, and regional values of the specific flow: (i) for the current baseline (experiment 1; Table II), the traffic multipliers for traffic increase between 2014 and 2019; (ii) for the future baseline (2a) the traffic multipliers for traffic increase between 2014 and 2017 and then using multipliers for the 'regulation and growth' for 2040 forecast [28]; (iii) for the high growth with technology future (3a) the traffic multipliers for traffic increase between 2014 and 2017 and then use multipliers for the 'global growth' for 2040 forecast [28].

Flows are represented as the number of seats an airline offers between an origin and destination (OD) pair and the aggregated number of passengers per itinerary and airline. The 2014 flows are then grown by the average of the multipliers for country/region of the origin and destination. In order to obtain the flows for experiment 2b, we need to overlay air traffic flows with the rail network. The analysis performed by the rail options generator in the rail layer modelling section provides the different options available to passengers using rail.

Rail can be used as a substitution of air travel or as a segment, *i.e.*, in multimodal itineraries. All flights with a great circle distance lower than 500 km are considered as potentially replaceable by rail if the HSR option exists. Demand flows which are only one-leg itineraries, *i.e.*, only one flight, which overlap with a rail alternative, are shifted to rail. For multi-leg itineraries, the rail mapping process will identify if the first or last leg can be performed by rail. If that is the case, these segments will be moved to rail. The model differentiates between rail stations at city centres and rail stations at airports, as the former will require the estimation of travel times from platform to kerb. After this process, if for a given origin-destination all passenger demand has been shifted to rail, the supply, *i.e.*, seats on flights, will also be removed, *i.e.*, the air link will be fully moved to rail. Finally, note that this strategic use of rail is only considered for rail routes within Spain, France, Italy and Germany.

C. Schedule mapper

The schedule mapper is based on the model developed in the strategic layer of the Vista model [30], and it produces the future schedules. The schedule mapper requires several inputs in order to generate future flight schedules: airport data; (historical) flight schedules; turnaround times, as the mapper adds not only the point-to-point flights, but creates rotations of added aircraft; aircraft data (*e.g.* aircraft leasing prices, aircraft ranges), as new aircraft need to be added to the schedules; supply data (*e.g.* number of seats per origin-destination), which comes from the generated flows for the Modus scenarios and experiments; airline data (*e.g.* type of airline). For each scenario flow (created as described in the previous sub-section) the schedule mapper produces individual airline schedules and planned flight rotations.

D. Passenger assigner

Once the previous modules are executed, the passenger assigner allocates passengers from the flow of passengers to flights creating individual passenger itineraries. This process is part of the pre-tactical layer. In order to generate passenger itineraries, the passenger assigner requires several inputs, including the origin-destination flight schedules generated by the schedule mapper, itineraries and airport data (*e.g.* coordinates, minimum connecting time). The assigner considers actual seat capacities sourced from external data. Not all passenger flows may be accommodated onto certain flights, and need to be redistributed, whereas other flights might be assigned unrealistically low load factors. The latter are mitigated with the generation of 'synthetic' (model-passive) passengers to ensure that realistic load factors are maintained. Overall only that part of the flows which are *air* are assigned to flights. However, full itineraries are maintained as part of longer, multimodal trips, starting or ending with a rail segment.

E. Rail layer modelling

A key part of this project is exploring the interconnectivity between air and rail. This multimodality is implemented through the development of a rail layer (rail options generator): a new layer of Mercury that allows us to exploit the MERITS database and find rail alternatives to the scheduled routes [23]. This can be done by a total substitution of air, or through a collaboration of both means of transport. The output of this module is a set of rail-based indicators for each possible direct rail route. The main information generated, which is later fed into the flow modifier and Mercury, is: average travel time, average waiting time, number of trains, and, time of the first and last train of the day.

1) Rail station-airport mapping: The first step towards adding rail options to the journeys is finding railway stations that can replace an airport. The criteria is based on distance: all the stations within 40 km of an airport are considered candidates. Although there is usually a main railway station that could be intuitively chosen as the replacement for the airport, reality is more complicated. Several European cities have multiple rail termini serving specific onward regions and countries (usually dependent on their geography within the city, such as being on the same side (as the destinations) of a major river bisecting the city; Paris and London are good examples). Others, less commonly, such as Brussels and Berlin, have most major locations served through a sequence of connecting stations (rather than termini). By considering all the stations within range, the approach is more robust since more possibilities are considered. In some special cases, there are important airports that have a railway station co-located at the airport. This draws on the archetypes assignments of Section IV-A. For such cases, that station is still considered a different node, allowing us to compute travel times from the airport to the city centre or directly to other cities.

2) Rail data processing: Once the rail stations are assigned to the airports, the next step is to find existing rail routes to substitute the air routes. Given the number of stations and all the possible rail links, the options have been limited to direct HSR connections. Each route has been processed to check whether it passes through any of the stations replacing an airport. Once this pre-processing is done, it is easy to extract all the trains connecting two given airports. For each train, the time of departure from the origin and the time of arrival at the destination are obtained, and therefore the travel time. Then, by taking into account all the intermediate stops, the distance travelled can be computed with higher precision than just taking the distance between the origin and destination. Finally, the average speed of the train is obtained from the previous metrics. This allows us to classify the trains as high-speed or regular (in experiment 2b we use only HSR lines, while for disruption simulation we use all possible connections).

3) Waiting time estimation: The average travel time is insufficient to model the expected time of door-to-door passenger itineraries. The expected waiting time plays a crucial role when using rail. This expected waiting time of a given route is obtained by first computing each of the waiting times from the ordered schedules. Then, the mean and the variance of that list of waiting times are computed. Finally, we calculate the expected waiting time from the previous metrics, to help determine the suitability of moving passengers to rail, during disruption.

4) Use cases: Once this layer is built, it can be applied to different subsets of the data to model the different cases: strategic route planning and tactical disruption management. In the strategic case, rail is used as a substitution and complement of air itineraries, either fully as replacement of the whole trip, or as a feeder to/from the hub in a multimodal context. This process is performed by the *Demand and supply flow modifier* presented previously (see Section IV-B). We limit the replacement of air by rail strategically to routes within Spain, Italy, France and Germany, as flagged, due to their extension and deployment of high-speed rail routes.

Two possibilities exist for these airports: either the railway station is located at the hub, or in the city centre. The strategic rail analysis differentiates between these two cases for each of the airports, *e.g.* , identifying destinations that can be reached directly from LFPG and those that are reachable from Paris requiring the transfer of the passenger from the airport to a major railway station in the city. This strategic rail analysis is used by the flow modifier (as introduced in Section IV-B). For these airports, the multimodal segments described in Table III will be estimated.

F. Tactical disruption

For the tactical disruption experiments (1*, 2a*, etc.) it is assumed that two regions are impacted by a large air disruption, and rail is used to route some of the affected passengers. All the rail schedules are considered, regardless of the countries involved, duration, or speed (high-speed rail or not). The regions of Madrid, with Madrid Barajas, and Paris, with Paris Charles de Gaulle and Paris Orly, are used. At these airports, 90% of short-haul (and 50% of long-haul) flights are cancelled, and modelled as if advised to all impacted passengers the day before (D-1), and operating (D) 0001-1400 (local time). The cancelled short-haul flights are compared to the rail network and the cities that can be reached directly by train. For experiments 1 and 2, these passenger trips are cancelled if no rail service is available, or if the rail journey takes more than twice as long as the original air trip. For experiment 3, this tolerance is extended to thrice the length, to reflect the fact that under this scenario new technologies render the rail option of a higher utility, notwithstanding the extra trip length. (The long-haul disruption is not yet modelled for any impacts.)

G. Mercury

As previously indicated, originally Mercury focuses on the modelling of the gate-to-gate (G2G) phase of the passenger itineraries. The model has been expanded to consider multimodal journeys. Mercury is a stochastic agent-based model [34]. The model considers agents to represent the main elements involved in the ATM system, among others: airline operating centres, flights, ground airports, E-AMAN, DMAN and the network manager. The model operates within a strong agent paradigm at the level of individual flights and passengers. It includes a realistic cost model for the airlines, allowing us to have a good tactical choice model and excellent estimation of airspace user costs. Due to the inclusion of different stakeholders, including passengers, and various processes – such as aircraft turnaround or passenger reaccommodation – it is able to capture European-wide network effects that are inaccessible to other models. Mercury can capture the non-linearities between delay for flights and passengers due to missed connections.

H. First and last mile (door-to-door modelling)

The D2D model combines the outcome of the different trip segments (see Table III). Following previous research [31], the kerb-to-door (door-to-kerb) and kerb-to-platform (platform-to-kerb) models consider the characteristics of passenger archetypes. These also consider the type of city (archetype), passenger and mobility options to estimate their expected travel times. Similarly, the kerb-to-gate (and gate-to-kerb) processes are modelled considering the type of passenger and airport, and various activities performed at the airport (kerb walk, luggage drop off (where applicable, according to the passenger archetype), security, immigration, buffer, baggage claim and passport control) [31]. These estimated times can then be combined with the intercity mobility metrics obtained from Mercury to build the full D2D estimated travel-time indicators.

V. Mobility model results

Looking at the first results, starting with Figure 4, the number of modelled flights and passengers carried by air is shown, by experiment, in the first two metrics columns. In the third column, whilst by definition all of the passengers (110 k) on the modelled short-haul banned (SHB) flights are shifted to rail (S2R) services, only just over 1% are not reaccommodated by train. The D2D times in the smaller SHB network (final column) are all logically lower than corresponding values (same rows) of the wider (176 airport) network. Of particular interest is the fact that, in both cases, the current (1a) and future (2a) baselines produce similar values, as do the SHB (2b) and future high growth (3a) experiments (the high growth with technology scenario includes modest improvements in D2K, K2G, G2K and K2D times by 2040). The data shown are currently missing elected buffer (wait) times, whilst we acquire these for rail journeys.

Figure 5 shows, for the same experiments as Figure 4, the CO_2 values per passenger (for the main rail and air modes travelled, *i.e.*, currently excluding airport access and egress). These are fairly uniform across the experiments, notwithstanding the improvements in emissions cited in Table II for air and rail by 2040. The 'flight wait' times (last two columns) reflect the average wait time for flights for passengers with connecting itineraries, taking into account minimum connecting times at airports. These improve (decrease) with traffic growth down the table, and are always smaller for the SHB countries (with or without the bans in operation).

Figure 6 shows some high-level results for each of the experiments in the previous figures with the disruption applied as described in Section IV-F, whereby the increased utility of rail in experiment 3 allows for a higher shift to rail (S2R; 17.5 k pax) and thus fewer (86%) cancelled trips. This rate is highest (97%) under the SHB, whereby air trips are longer on average and more difficult to replace by rail. The CO_2 'saved' per passenger as a result of the disruption-cancelled short-haul flights across all experiments, taking into account the corresponding emissions for those substitute rail journeys that are possible, is quite uniform. This fairly indicative metric currently excludes airport access/egress, transfer modes, and, indeed, the social cost of the cancelled trips.

VI. Future Research

The research presented in this paper provides an innovative approach towards data-driven, integrated air-rail modelling, considering passenger door-to-door itineraries. The modelling is founded on a set of diverse scenarios, and facilitated through the use of archetypes and modal choice sub-models, extending the state of the art to regional, cf. city pair, analyses. In further development of this work, we are currently calibrating some of the outputs against other models, *e.g.* EUROCONTROL's R-NEST tool. We also anticipate the integration of these models with a multimodal performance framework, building solutions

Exp. #	Description	Disruption	Air	Rail	Key metrics: Flights	Air pax¶	Pax S2R / Cancelled pax	Network D2D average¶	Short-haul ban states D2D average†¶
1	Current baseline	×	2019 traffic	2019 network	31 080	4 029 k *1 950 k*	-	*467 mins*	*422 mins*
								≈	≈
2a	Future baseline	×	2040 base growth	2040 network	44 900	5 920 k *2 720 k*	-	*469 mins*	*424 mins*
2b	2a + short-haul ban†	×	2040 base growth	2040 network	1360 banned	*110 k* banned	= *110 k* *1.6 k*‡	*445 mins*	*402 mins*
								≈	≈
3a	Future high growth	×	2040 high growth	2040 network	52 200	7 190 k *3 220 k*	-	*439 mins*	*394 mins*

† Values in this row/col refer to the four countries in which the short-haul ban is applied (GCD < 500 km not operated by air in DE/FR/ES/IT, *where rail alternatives exist*)
¶ Values in italics refer to passengers travelling on the OD pairs within the 176 European airports for which Modus applied city/airport archetypes
‡ Cancelled due to exceptional circumstances, e.g. substitute air-rail-air itineraries being impractical

Figure 4. Traffic and passenger flows with D2D averages

Exp. #	Description	Disruption	Air	Rail	Key metrics: Air pax¶	G2G network CO_2	G2G short-haul ban states CO_2 †	Network flight wait	Short-haul ban states flight wait †
1	Current baseline	×	2019 traffic	2019 network	4 029 k *1 950 k*	94 kg/pax	99 kg/pax	149 mins	122 mins
2a	Future baseline	×	2040 base growth	2040 network	5 920 k *2 720 k*	86 kg/pax	91 kg/pax	133 mins	112 mins
2b	2a + short-haul ban†	×	2040 base growth	2040 network	*110 k* banned	87 kg/pax	92 kg/pax	137 mins	112 mins
3a	Future high growth	×	2040 high growth	2040 network	7 190 k *3 220 k*	85 kg/pax	89 kg/pax	125 mins	101 mins

† Values in this row/col refer to the four countries in which the short-haul ban is applied (GCD < 500 km not operated by air in DE/FR/ES/IT, *where rail alternatives exist*)
¶ Values in italics refer to passengers travelling on the OD pairs within the 176 European airports for which Modus applied city/airport archetypes

Figure 5. Passenger flows with G2G CO_2 and flight waits

Exp. #	Description	Disruption	Air	Rail	Key metrics: Flights cancelled	Air pax cancelled	Pax S2R	Cancelled pax	CO_2 saved
1*	Current baseline	✓	2019 traffic	2019 network	898	69.8 k	4.81 k	93 %	20 kg/pax
2a*	Future baseline	✓	2040 base growth	2040 network	1460	104 k	7.27 k	93 %	19 kg/pax
2b*	2a + short-haul ban†	✓	2040 base growth	2040 network	1170	95 k	3.14 k	97 %	20 kg/pax
3a*	Future high growth	✓	2040 high growth	2040 network	1530	122 k	17.5 k	86 %	18 kg/pax

* These experiments are subject to disruption.
† Values in this row refer to the four countries in which the short-haul ban is applied (GCD < 500 km not operated by air in DE/FR/ES/IT, *where rail alternatives exist*)

Figure 6. Disruption flows with cancelled pax and CO_2 saved

at higher technology readiness levels with a specific focus at the strategic (*e.g.* scheduling) and tactical (*e.g.* disruption) phases. Challenges overcome within Modus, not least the extrapolation of supply-side delivery in the air and rail sectors to future scenarios, under given economic and other exogenous contexts, will strengthen and inform such future research. The modelling in Modus is thus anticipated to form the basis of a multimodal evaluation tool, critically capable of quantifying new policy impacts, which are often implemented in the absence of such an assessment.

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