# Evaluation of Passenger Connections in Air-rail Multimodal Operations

Michal Weiszer, Luis Delgado, Gérald Gurtner
Centre for Air Traffic Management Research
School of Architecture and Cities
University of Westminster
London, NW1 5LS, United Kingdom
m.weiszer@westminster.ac.uk

***Abstract*—Efficient cooperation between transport stakeholders (airlines, rail and airport operators) is essential for improved multimodal journey times and passenger experience, ensuring their connectivity, particularly during disruptions. There is a need for a platform where solutions supporting multimodality can be evaluated.**

**This paper presents the extension of Mercury, a detailed open-source air transport agent-based model, to include rail network modelling capabilities, enabling the evaluation of multimodal itineraries. New agents are introduced to simulate train operations (arrivals, departures), to handle multimodal transfers, to represent airport processes, and to rebook passengers when connections are missed. By modelling processes during transfers even when the infrastructures are not collocated (*e.g.* ground mobility between the train station and airport, processes inside the airport), solutions for improving multimodal connections, such as expedited airport processes for delayed passengers, can be evaluated. Thus, the new simulation platform is a multimodal modelling and evaluation tool that comprehensively describes the impact of solutions (or policies) to support multimodal journeys.**

**Due to the buffers on multimodal itineraries, even in the case of disruptions, many missed connections are caused by just a few minutes. In this context, two mechanisms are modelled and evaluated for a multimodal operational environment set in Madrid: prioritising delayed passengers in airport processes, which can significantly reduce missed connections and total experienced delays; and a more reliable dedicated bus line linking the air and rail infrastructure, which would make the connection between modes more convenient and can also contribute to reduced missed connections.**

***Keywords*—Agent-based model, multimodal air-rail transport, performance assessment, delay management, passengers**

## I. INTRODUCTION

Multimodality is considered one of the key elements for creating an efficient and interconnected transport system within Europe that can help to achieve the goals of the Paris Climate Agreement [1]. The cooperation of individual transport modes is crucial for the overall system's performance, especially during disruptions. However, current research lacks platforms for evaluating multimodal system performance.

The air transport domain has historically focused on the improvement of flight operations. However, as shown in previous research, passengers can experience their mobility very differently from the performance of individual flights [2]. This is particularly relevant when considering the total passenger journey (door-to-door), which can be largely impacted by connections along the journey. Missed connections can easily lead to very high total delay experienced by the passengers, as the next available service could be several hours later, or they might even end up stranded. Multimodal journeys, by construction, require connections across modes that are not necessarily coordinated; in this article, we will focus on modelling these connections and providing a tool to evaluate mechanisms to support them strategically (with more reliable links) and tactically (to deal with delays).

Modelling passenger itineraries connecting multiple modes brings additional challenges, as illustrated in Figure 1.

In a monomodal connection (*e.g.* air-air as in Figure 1a), passengers transfer from one gate to another inside the airport and might be impacted by disruptions affecting flights.

In multimodal connections (*e.g.* air-rail/rail-air in Figure 1b), if the rail station is located at the airport, passengers can walk to the gate (or the train station) going through additional processes (*e.g.* check-in, security). In this case, the connection can be impacted by disruptions on trains, flights and the airport passengers' processing elements. However, the connecting time required between modes is expected to be reliable. Unfortunately, very few airports in Europe have a long-distance rail infrastructure embedded in them (*e.g.* Paris-Charles de Gaulle, Amsterdam-Schiphol, Frankfurt), and the number of destinations that can be reached directly can also be limited. This means that extending air-rail multimodal journeys, considering that the rail station is located away from the airport[1], could bring some benefits, albeit some challenges.

As depicted in Figure 1c), when connecting modes which are not collocated, passengers must use additional ground mobility services, such as metro or bus. These connections can require longer and more uncertain transfer times as passengers might be unfamiliar with the infrastructure, and the modes can be more unreliable and prone to disruptions. In this case, as shown, considerably more components need to be modelled to evaluate the impact of dedicated mechanisms to support these transfers (*e.g.* dedicated high-frequency lines linking the airport and rail stations) or to reduce potential missed

---

[1] Note that there may be multiple rail stations accessible from the airport that could be part of these multimodal trips.

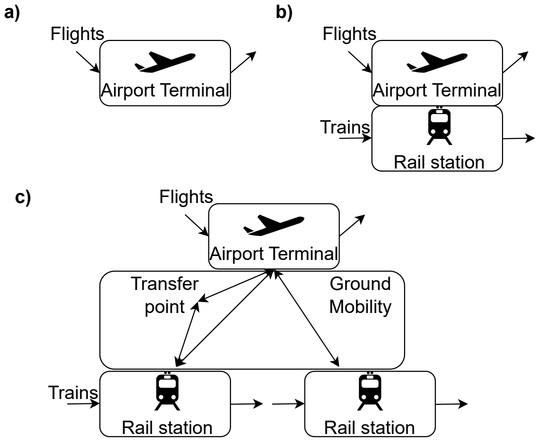


Figure 1. Connection types: a) monomodal, b) multimodal with rail station at the airport, c) multimodal with rail stations in the city.

connections (*e.g.* with faster processing time for disrupted passengers at airports).

This study extends the open-source Mercury simulator platform [3] to include multimodal (air-rail/rail-air) itineraries. Mercury features a detailed description of the air transportation system at the European level, including passengers, aircraft, and various important actors such as the Network Manager, airports, etc. Its agent-based paradigm is exploited to add new agents to achieve multimodal capabilities. The new agents represent train operations (arrivals and departures), passengers' journeys between the modes during the multimodal transfers, and the passengers' processes at the airport. This enables Mercury to simulate multimodal passengers' itineraries starting and ending at either an airport or a rail station.

The extended Mercury provides a performance assessment tool that is usable early in the innovation pipeline to better estimate the impact of new changes to the air transportation system, particularly with a combination of other transport modes. Mercury can provide a comprehensive view of how individual mechanisms contribute to the system's performance.

A multimodal case study set in Madrid-Barajas airport with a two-and-half-hour flight ban in Spain is considered. Disruptions on the ground mobility linking the airport and the rail stations are modelled to assess the benefits of:

- The effect of service interval of ***a dedicated bus line*** between air and rail infrastructure.
- Prioritisation of delayed passengers at the airport with a ***Fast-track process*** to reduce the number of missed connections impacted by disruptions.

## II. BACKGROUND

Different *mechanisms* are used or have been researched to minimise the impact of disruptions for multimodal passengers; Section II-A summarises some of these. Section II-B presents the required background on the Mercury mobility model.

### *A. Previous research on disruption management*

The review below briefly describes some of the main actions for managing disruption that could be performed in the air system and compares them with their rail counterpart. Multimodal disruption mechanisms (that consider multimodal itineraries) are also briefly presented.

This list of air disruption management mechanisms builds upon [4]–[6]; and a comprehensive review of rail disruption management approaches can be found in [7].

The main mechanisms at the disposal of operators to manage disruptions are:

- Modifying their planned operations by *Actively delaying flights and trains* to wait for connecting passengers, *Rerouting* to avoid congested areas and/or *Speed controlling / Trajectory updating* to recover part of the delay;
- managing their resources by *Cancelling services* to release resources, *Swapping* and *Reassigning vehicles* to operations, using *Reserved resources* if available, and repositioning them with *Deadheading and ferrying* operations.
- In addition to these, rail operators also consider actions such as *Reordering*, where trains are swapped on their use of the infrastructure (rail tracks), *Short-turning* and *Stop-skipping*, where either some stops are not served to expedite the service or the rail service finishes before reaching their final destination.

The infrastructure can also be modified to mitigate the impact of disruptions with actions such as:

- *Enhancing ATM systems* to reduce airspace and or airport congestion, for example, with fast turnaround operations and optimising gate allocation; and providing flexibility to operators such as sequencing mechanisms and ATFM slot swapping (*e.g.* User Driven Prioritization Process (UDPP)) [8]–[10].
- Similarly, at rail stations *Replatforming* can be used to manage the capacity.

Besides the operations and resources, managing the passengers' itineraries is paramount to ensure they reach their final destination when disruptions impact them. This is done with *Passenger reallocation* processes.

Due to the distributed nature of airline operations, most studies that aim to minimise the impact of disruptions in the system consider the optimisation problem from an Airline Operating Centre point of view, modelling the airline resources and constraints.

Airports are the nodes in the air transport system where the impact of disruptions is materialised by operators and passengers; moreover, many of the mechanisms that could be put in place are applied within their scope. Therefore, when modelling disruption management at airports, most studies consider airport constraints such as simultaneous numbers of take-offs and landings or time windows for airports [6]. Airport resources, such as resources for ground operations assignment, can then be considered as decision variables, such as in [11].

There is a small amount of literature on disruption management of multimodal air-rail systems. Most studies focus on integrated passenger reallocation considering multiple modes (*e.g.* air-to-rail) in case of disruptions [12], [13]. Improved information sharing to passengers [14] and collaborative decision making [15] are also employed. The work presented in [16] shows how actively delaying flights can be used to minimise multimodal rail-air passengers' missed connections in the event of rail disruption. An example of a strategic measure such as air-rail timetable synchronisation is in [17].

Previous research has also shown how landside airport processes (*e.g.* security check allocation) can play an important role in managing delayed passengers in a multimodal environment, *e.g.* when passengers arriving at the airport are delayed on their rail journey [18].

Regarding the methodology used, most studies adopt exact, heuristic or hybrid methods to solve the optimisation problem in a centralised way. In contrast, Multi-Agent Systems (MAS) is an emerging approach in airline disruption management employing distributed optimisation with multiple interacting intelligent agents. This enables the modelling of partial information to be considered when dealing with disruptions and the allocation of responsibilities to actors, which can more closely represent the nature of the operational environment. Examples of MAS include [17], [19], [20].

### B. *Mercury: An Agent-Based Model for air transport mobility*

Evaluating the performance of a complex system like air transport is a challenging task. Uncertainty, disruptions, and the interaction of many actors drive the system's performance. Agent-based modelling (ABM) can tackle these types of systems. In these platforms, the decisions of each agent can be modelled individually with relatively simple rules.

The open-source Mercury simulator[2] has been developed with these considerations over different research projects to estimate flight and passenger-centric indicators [3]. Mercury incorporates the processes and behaviours of actors in air transport. The model has successfully been applied to a range of problems, such as the assessment of SESAR Solutions [21].

The event-driven approach of Mercury, with events associated with flight milestones, such as 'Push-back' or 'Flight arrival' times, enables a fast-time simulation of a day of operations in the whole of the ECAC[3] region in a few minutes.

Mercury models the main activities performed in the system as *roles* with interactions between them. These are then grouped into *agents*; this process was guided by existing entities in the ATM domain, where naming and representation would refer to a coherent actor/entity (such as the Airline Operating Centre (AOC)).

The following agents are represented in Mercury (also depicted in Fig. 2):

- 'Airline Operating Centre': They are tasked with the airline's fleet management (*i.e.*, dispatching processes), including the management of flight plans, flight cancellations and passenger rebooking for air-air connections.
- 'Flight': Represent the flight along its ground and air operations. These agents also capture the actions performed by the crew, such as requesting a departing slot.

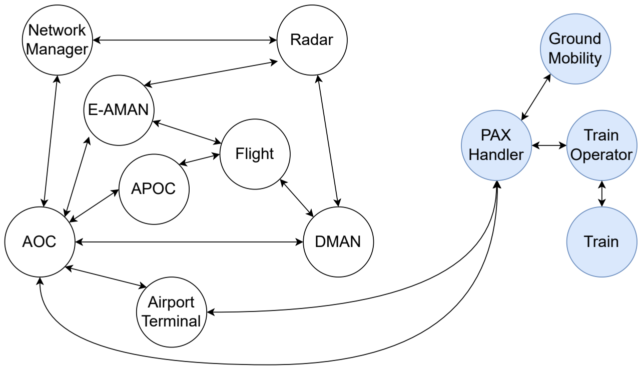


Figure 2. Acquaintances between agent types, derived from interactions between their underlying roles.

- 'DMAN' and 'E-AMAN': Each airport has associated 'DMAN' and 'E-AMAN' agents to manage the departure and arrival queue of slots needed to respect the runway capacities.
- 'Radar': This agent broadcasts the flight position to all other interested agents.
- 'Network Manager': There is a 'Network Manager' agent per simulation with a simplified view of the European airspace and ATFM restrictions.
- 'Airport Operating Centre' (APOC): One per airport models and manages the airside operations, providing planned and actual turnaround times.
- 'Airport Terminal': complements the APOC by modelling the connecting times between flights for connecting passengers, and the passengers' access and egress processes, *e.g.* check-in and security time.

Mercury's agents react to events triggered by other agents or the environment (events). An agent might require interaction with others in a message-driven approach. The interactions depend on the implemented operational concept. For example, the APOC and Airport Terminal agents deal with flights and passengers, respectively, and thus do not interact with each other directly in this implementation of Mercury.

It is worth noticing that passengers are represented by passengers' groups with the information on their planned itinerary, *i.e.*, flights/trains that are planned by that group. These are processed by the different agents in the system as needed, *e.g.* the AOC will board the passengers into flights.

Mercury can evaluate ATM Solutions by modifying the behaviour of the system's elements. This is achieved either by modifying the functionalities within agents' roles using *modules*, or by connecting Mercury with external systems by redirecting the inter-agents messages to an external interface (currently under development).

## III. MODELLING APPROACH

### A. *Multimodal passengers itineraries and processing*

This article considers two types of multimodal itineraries: 1) rail-to-air and 2) air-to-rail. Monomodal connections from air-to-air are already part of Mercury, and monomodal connections

---

[2] Mercury repository: https://github.com/UoW-ATM/Mercury

[3] European Civil Aviation Conference (with 44 Member States).

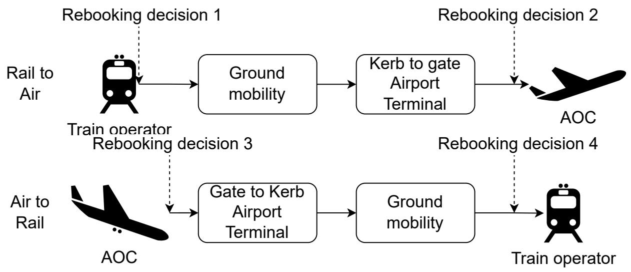


Figure 3. Multimodal processes.

from rail-to-rail are out of the scope of this study. It should be noted that other types of more complex itineraries, such as rail-to-air-to-rail, etc., are possible by simply chaining the before-mentioned types.

Following the approach described in [22], passengers' itineraries are divided into differentiated processes to build the full multimodal journey. For example, a rail-to-air multimodal trip can be modelled by concatenating the platform-to-platform, platform-to-kerb, kerb-to-gate, and gate-to-gate processes. Note how Mercury is able to compute the gate-to-gate times, including any possible flight-to-flight connection.

Fig. 3 represents the flow of a passenger for the two types of multimodal journeys considered:

- The rail-to-air flow starts with deboarding the train. Next, the passenger moves from the rail station to the airport. The passenger travels from kerb-to-gate in the airport terminal, going, as required, through baggage drop, airport security, etc. Finally, the passenger boards the aircraft.
- The air-to-rail flow is similar to the rail-to-air flow, with processes in reverse order. Gate-to-kerb in the airport terminal will consist of the processes of collecting the baggage, immigration, passport control, etc., as required.

### B. *Mercury evolution for multimodality*

Some agents have been modified, and others have been added to Mercury to enable the simulation of the multimodal journeys previously described. Fig. 2 shows the acquaintances (connections) between agent types derived from interactions between their underlying roles. The newly added multimodal agents are highlighted on the right.

In the agent-based model paradigm, it is important to establish which actor makes the different decisions and based on which information. Therefore, defining an operational concept is paramount when modelling the different involved processes. It can be considered that passengers lack any decision capability in the current air system as they are directed by other agents during their gate-to-gate journey (*e.g.* in case of missed connections, airlines will rebook passengers to flights on their behalf). However, in a multimodality paradigm, it is expected for passengers to have a more active role at some points during their journey, *e.g.* deciding if a connection is going to be missed prior to initiating the transfer between modes and initiating a rebooking process before travelling, or finding their way on the ground mobility while transferring between modes. For this reason, as seen in Fig. 2, the 'Passenger Handler' agent has a central position on multimodality, facilitating most of the interactions between other agents. Next, we describe the new agents and multimodal roles incorporated into Mercury.

*1) Passenger handler:* The 'Passenger Handler' agent represents the decision processes of a passenger. From an architectural point of view, there is a single 'Passenger Handler' agent in the simulation that manages passenger groups. Passenger groups are modelled as simple placeholders which contain information on the passenger itineraries and their characteristics. The 'Passenger Handler' agent moves the passenger groups through different processes facilitated by other agents during the rail-to-air or air-to-rail connection.

As mentioned above, there are two rebooking decision locations as indicated in Fig. 3:

1) After deboarding the train/aircraft of the first leg (Rebooking decisions 1 and 3 in Fig. 3). The 'Passenger Handler' agent collects the estimated ground mobility and kerb-to-gate times, together with the estimated departure time of the next leg. If the connection is deemed to be likely missed (based on the gathered estimated times), the 'Passenger Handler' will make the rebooking decision. This way, the passengers can change their itinerary based on the actual situation, considering the already accrued and onward estimated delays. The rebooking process involves finding the next available flights/trains for the remaining part of the itinerary. In this study, the rebooking process chooses the first available service with sufficient capacity within the originally planned mode.
2) Before boarding the train/aircraft of the next leg (Rebooking decisions 2 and 4 in Fig. 3). The same rebooking process as in 1) is initiated after arriving at the gate/platform after the next flight/train has already departed. The Rebooking decision 2 at the gate is made by the AOC, as in the case of air-air connections, which are the airline's responsibility. The Rebooking decision 4 in this paper is made by the 'Passenger Handler' as it is currently the case when rail connections are missed. Note that the responsibility for rebooking could depend on legal arrangements such as single ticketing.

*2) Train:* The 'Train' agent models the processes related to the operation of train services, mainly arriving and departing from stations. An initial delay which occurs with a given probability is modelled as a probabilistic distribution.

*3) Train operator:* The 'Train Operator' keeps track of the arrivals and departures of trains and any train delays. It manages the boarding and deboarding of passengers and, in case of missed connections, can find the next direct train. In this study, we assume sufficient capacity for trains.

*4) Ground mobility:* The 'Ground Mobility' agent provides the estimated and actual connection times between the rail stations and airports and vice versa. There is only one 'Ground Mobility' agent in the simulation. Passengers could take different modes of transport (bus or metro in this study). These times are modelled as probabilistic distributions estimated using Google Maps and considering public transport transfer times during the day.

*5) Airline Operating Centre:* The AOC considers multimodal passengers to be like any other passengers. For passengers who missed an air connection but are already at the airport, a reallocation process to the next flight considers their itineraries, aircraft space, and fares.

*6) Airport terminal:* The 'Airport Terminal' agent captures the processes of passengers within the airport. For passengers connecting air-to-air, the agent provides connecting times between gates. For multimodal passengers, the agent provides kerb-to-gate (baggage drop, airport security) and gate-to-kerb processes (baggage collection, immigration) for rail-to-air and air-to-rail passengers, respectively. These processes are modelled as probabilistic distributions.

## IV. CASE STUDY

### A. *Scope of study*

A day of air traffic on $22^{nd}$ September 2023 has been used as an example for the analysis, with flights arriving/departing to/from Madrid Barajas (LEMD) (816 flights in total).

For the rail network, an open GTFS dataset from Renfe (Spanish Public Rail Service Operator) containing information on long and medium-distance rail services at high and conventional speeds is used. All possible direct rail trips between the cities next to airports in Spain are extracted, as in [23]. The train times are modelled according to their timetable with some added noise in the simulation. An initial delay of mean 0 and standard deviation of 5 minutes is applied to all trains. The modelling approach is that the trains are delayed at the source, and this delay is propagated through their service.

A flight ban for short-haul flights is imposed to generate multimodal itineraries. All flights with at least a rail alternative faster than 2h30 are removed. The fastest services between all origins and destinations are identified to assess if this threshold is breached. For example, between Valencia (LEVC) and Madrid (LEMD), at least a train service takes 1h50. Therefore, all flights between the two cities are removed. This 2h30 threshold is in line with the proposed ban by the Spanish government [24]. In the proposed regulation, only flights to *non-connecting* airports will be affected, similar to the equivalent French regulation [25]. In this article, however, we ban all flights within the threshold. This means that passengers with connecting fights whose journey required a short-haul flight that is now cancelled will become multimodal passengers. Following the analysis performed in [23], 71 flights are cancelled (with a remainder of 745 operated flights), and 154 rail services are used to maintain the same connectivity. The strategic impact of this ban is out of the scope of this research. For example, schedules are not optimised but maintained as originally, and some itineraries might not be valid anymore if the rail timetable does not match the air connectivity.

The possible connections between flights and between modes are based on the connectivity that was originally possible in the air network with the same restrictions as in [23]. When considering multimodal itineraries, connecting times between rail stations and airports and modelling the processes at the airport from their kerb to their gates are required.

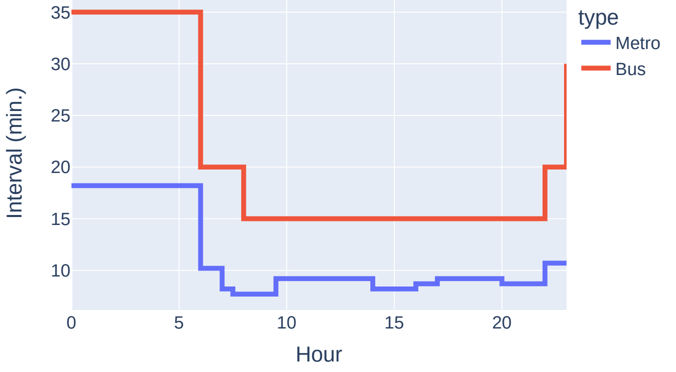


Figure 4. Ground mobility interval.

The kerb-to-gate (114 min.) and gate-to-kerb (32 min.) mean times are used to model the airport terminal processes. These values are taken from Modus report [26].

### B. *Ground mobility*

The ground mobility between two main rail stations (Atocha, Chamartin) and the LEMD airport is assumed to be 1) metro with a transfer to commuter train (denoted as metro) or 2) a direct dedicated bus (Line 203). Mean ground mobility times are obtained by exploring Google Maps: 45 min metro or 40 min bus to Atocha, and 22 minutes (metro) to Chamartin. At present, there is no direct bus from the airport to Chamartin. The ground mobility journey time is greatly affected by the waiting time for the service, depending on the interval during the time of day, as shown in Fig.4. Note that in the case of 1), the final interval is a sum of metro and commuter train intervals. The waiting time for passengers between services is modelled as a uniform distribution within (0,*interval*). The travelling times are assumed to be symmetric, *i.e.*, the same between the rail station and airport and vice versa.

### C. *Passenger itineraries*

The above values are used when estimating which connections between rail services and flights are possible, as in [23]. Note that the most *efficient* connection is only kept. A given flight (or train) could connect with several onward trains (or flights) going to the same final destination; the approach keeps only the fastest alternative, which respects the average connecting times. On the one hand, this avoids going to the train station to wait for a service when an earlier one could be used; on the other hand, this means that the buffers used by passengers are the shortest possible given the schedules and timetables available. It is worth noticing that these schedules and timetables have not been optimised to minimise these waiting times.

Once flight, trains and their possible connectivity are defined, the services are populated with passenger itineraries. Aggregated air passengers' itineraries (including multi-leg

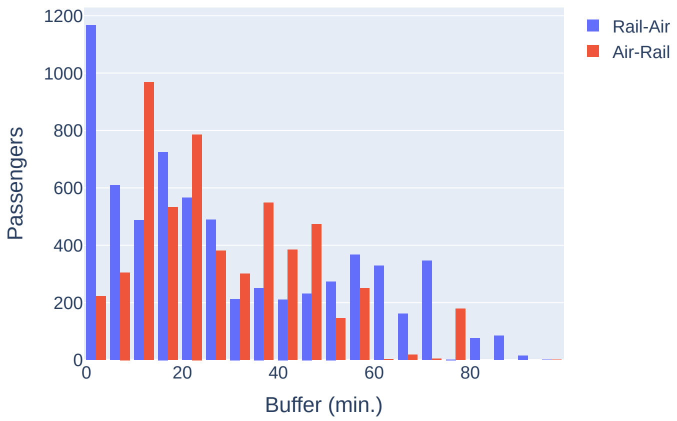


Figure 5. Itinerary buffers in 5 minute intervals.

journeys) data for September 2019 from AviationWeek[4] are used for the demand. These passenger flows are disaggregated into the flights and train services to accommodate the maximum number of passengers from the September 2019 demand, generating individual passengers' itineraries.

Note that the starting point is the air demand, and this has been tried to be satisfied with the new multimodal network. Changes in demand due to the change in the nature of the journey (from solely air to multimodal) are not captured. The total number of assigned distinct passenger itineraries is 8,341, with 89,734 total passengers, out of which 12,911 are multimodal. The passenger flows are analysed in more detail in Tab. I according to their origin/destination. Most multimodal passengers use LEMD to connect flights to/from ECAC airports. 66.8% of the passengers are single-flight passengers to/from Madrid, 18.8% are connecting between two flights at Madrid, and only 14.4% are multimodal, with slightly more passengers getting a train to the airport to connect with a flight than the other way around.

As previously mentioned, the most efficient connections are used, *i.e.*, with minimum waiting times, but the air schedules and rail timetables are not optimised in any form. Fig. 5 shows these itinerary buffers, *i.e.*, extra time between legs after substracting mean ground mobility time, kerb-to-gate and gate-to-kerb times. As can be seen, many passengers have small buffers (*e.g.* less than 5 min.) and these will be most likely affected by any disruption.

Finally, nominal (with ground mobility running close to their timetables) and disrupted conditions (with delays in the ground mobility) experiments are defined. In the disrupted case, all ground mobility is set to be delayed by 10 or 30 minutes. This is similar to the assumption done in [16].

### *D. Mechanisms evaluated*

Two mechanisms are evaluated:

*1) Dedicated bus line with adjusted frequency of service:* A *dedicated bus line* can make the intermodal connection more attractive by eliminating transfer using metro and commuter trains and more reliable as the waiting time relies on only one distribution (in contrast to two for metro and commuter train). This is particularly relevant when the train stations are not adjacent to the airport, as passengers will prefer a simple and reliable connection between both modes. This bus line is modelled using the real timetables of Line 203 between Atocha rail station and the airport. We assume a new bus line to Chamartin with the same interval as Line 203 and travel equal to metro journey time (22 minutes)[5]. The bus interval is then either the original or reduced by 5 or 10 min.

*2) Fast-track pre-departure:* A *Fast-track* to process passengers at the airport pre-departure is used as a tactical disruption management mechanism. The airport could implement this in different ways, such as reducing the processing time at security checks (dedicated lane, more staff) as in [18], faster baggage drop or tactical gate change to shorten walking distance. In this simplified version, multimodal delayed passengers can use a dedicated Fast-track, which reduces their kerb-to-gate processing times at the airport by a specified ratio.

The 'Passenger Handler' requests the 'Airport Terminal' the time required to perform the kerb-to-gate. In the nominal situation, *i.e.*, without the Fast-track mechanism, the 'Airport Terminal' will return the value independently of the passenger's situation. When the Fast-track mechanism is in place, the 'Passenger Handler' includes information about the passenger's status in the request message, *i.e.*, if the passenger is delayed or not. The 'Airport Terminal' then provides either the nominal kerb-to-gate time or a 0.4 faster time (*i.e.*, 60% of the nominal value). This speed-up coefficient is consistent with the results presented in [18]. For simplicity, only the metro is used in the ground mobility in this experiment.

This Fast-track mechanism can be implemented with two different approaches in Mercury: 1) as a module of the 'Airport Terminal' agent, which replaces the 'Wait for move kerb2gate times request' role; 2) as an external system which receives a message from the simulation. An external system enables the detailed modelling of the airport processes outside Mercury using dedicated tools if desired.

## V. RESULTS

This section presents simulation results obtained by running Mercury with implemented multimodality and mechanisms. Each run is repeated 10 times to obtain representative results. A baseline scenario represents Mercury with metro and without the disruption management mechanism.

### *A. Dedicated bus line*

Fig. 6 shows the number of passengers with missed connections as a function of the type of connection and the ground mobility disruption. The reduced interval bus experiments result in a lower number of passengers with missed connections under all disruption conditions compared to the bus

---

[4] https://aviationweek.com/ (Accessed on September 2024)

[5] This time is compatible with 'driving' times according to Google Maps.

TABLE I. ORIGIN AND DESTINATION OF PASSENGER FLOWS AT LEMD.

| Passengers | where XXXX is<br>non-ECAC | <br>ECAC | <br>Spain | Total |
|---|---|---|---|---|
| Single incoming air XXXX-LEMD | 7,421 (8.3%) | 14,538 (16.2%) | 8,463 (9.4%) | 30,422 (33.9%) |
| Single outgoing air LEMD-XXXX | 4,874 (5.4%) | 14,945 (16.7%) | 9,742 (10.9%) | 29,561 (32.9%) |
| Connecting air-air incoming XXXX-LEMD-YYYY | 493 (0.5%) | 6,060 (6.8%) | 10,287 (11.5%) | 16,840 (18.8%) |
| Connecting air-air outgoing YYYY-LEMD-XXXX | 2,823 (3.1%) | 6,103 (%6.8) | 7,914 (8.8%) | 16,840 (18.8%) |
| Multimodal air-rail (incoming) XXXX-LEMD-train | 336 (0.4%) | 4,904 (5.5%) | 477 (0.5%) | 5,717 (6.4%) |
| Multimodal rail-air (outgoing) train-LEMD-XXXX | 2,722 (3.0%) | 3,913 (44.4%) | 559 (0.6%) | 7,194 (8.0%) |

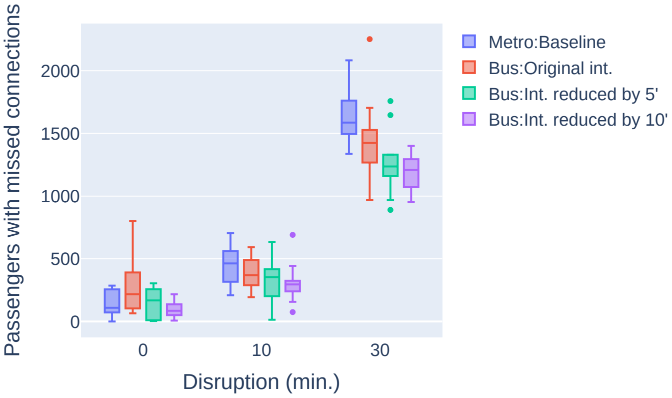
Percentage with respect to total passengers (89,734). Note connecting air-air passengers are double counted in the table, hence total percentage $>$ 100

with the original interval and metro. In 30-minute disruption, reducing the interval by 5 and 10 min decreases the missed connection passengers by 13% and 15% for rail-to-air and 7% and 14% for air-to-rail, respectively. The differences in results are more pronounced with higher disruption. Interestingly, the results for metro and bus with the original interval are similar. The journey to Atocha by bus is faster than by the metro by 5 min. and thus compensating for the longer intervals, making the ground mobility time shorter for the bus compared to metro in peak times (off-peak metro is better). There are relatively many passengers missing a connection even with no disruption. As explained above, the itineraries were generated using deterministic average connecting times and schedules. As such, adding stochastic noise during simulation causes some connections to be missed. This highlights the need for dedicated mechanisms to support (and improve) the connections during the day of operations.

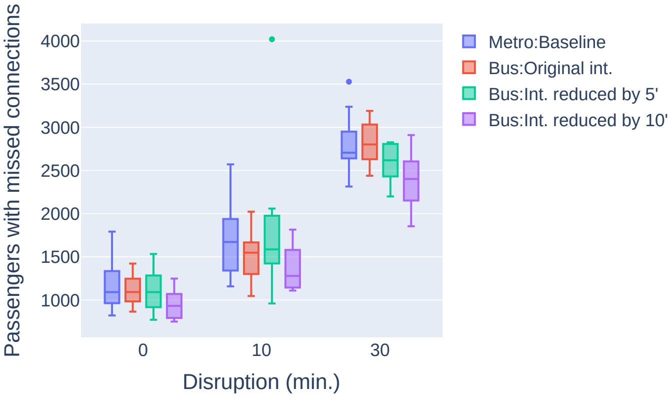
### B. *Fast-track pre-departure*

Fig. 7 shows the number of passengers with missed connections during disruption. As can be expected, with higher disruption, the number of missed connection passengers increases. For rail-to-air connections, the *Fast-track pre-departure* disruption management mechanism with 0.4 speed-up coefficient helps to keep the number much lower compared to baseline even with higher disruption. An 87% reduction is achieved for the 30-minute disruption. For air-to-rail connections, the values are very similar (with Fast-track vs without), as the mechanism only affects the kerb-to-gate times and, therefore, does not impact those passengers. Other metrics also captured by Mercury, such as the total arrival delay or number of stranded passengers, show similar trends and are omitted due to space constraints.

Fig. 8 shows the number of missed connections for a 30-minute disruption with a varying Fast-track speed-up coefficient. As expected, a smaller coefficient and thus kerb-to-gate time for delayed passengers reduced the metric. Each reduction of kerb-to-gate time by 10% (around 11 minutes for LEMD) reduces the number of missed connection passengers by more than 50%, except for the last coefficient of 0.4, which has a similar performance to 0.3. This could be explained by a diminishing number of rail-to-air passengers who can benefit from further reduction of kerb-to-gate times in accordance with the shape of the distribution of itinerary buffers.



(a) Rail-to-air.



(b) Air-to-rail.

Figure 6. Missed connections with a dedicated bus line.

## VI. CONCLUSIONS AND FURTHER WORK

This paper presented a new simulation platform based on Mercury to comprehensively describe the impact of multimodal solutions for delay mitigation. Mercury was extended with new agents to consider multimodal passenger itineraries and several mechanisms to facilitate multimodal journeys and cope with disruptions in the system were evaluated (a dedicated bus line and airport Fast-track).

Simulation experiments with a Madrid-Barajas case study assessed the benefits of the mechanisms, focusing on passengers' metrics (missed connections). For air-to-rail connections, *a dedicated bus line* with reduced intervals by 5 and 10 min

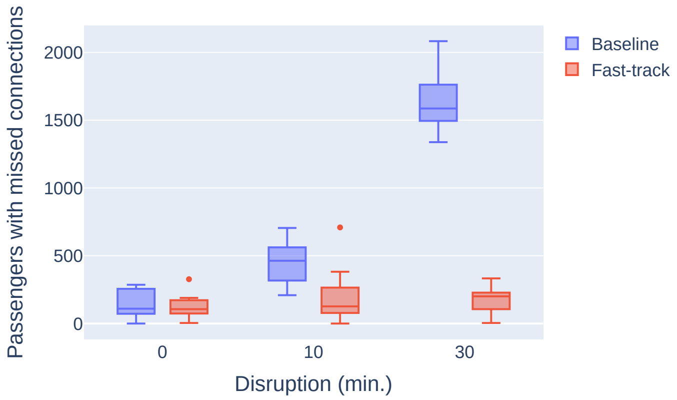


Figure 7. Missed connections passengers with 0.4 speed-up coefficient.

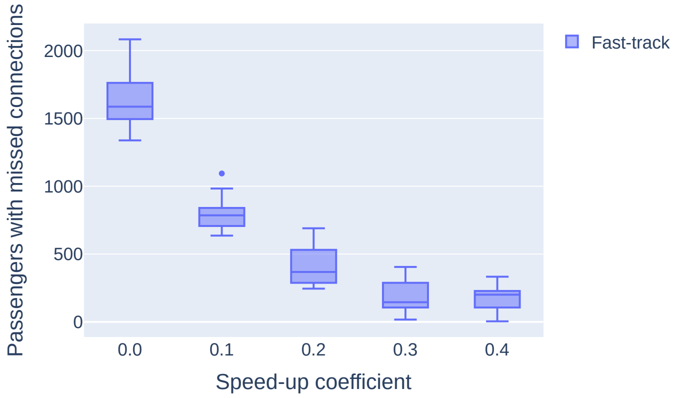


Figure 8. Experiment with different Fast-track speed-up coefficient.

decreased the missed connection passengers by 13% and 15% for rail-to-air and 7% and 14% for air-to-rail, respectively, during 30-minute disruption. For rail-to-air connections, the *Fast-track pre-departure* achieved an 87% reduction of missed connections during the 30-minute disruption. Experiments with varying speed-up of Fast-track showed that significant benefits (more than 50%) in terms of rail-to-air missed connections can be achieved even with 10% speed-up.

Mercury's flexibility, modularity and design enable many different modelling improvements to capture the characteristics of multimodal journeys with more detail. For example, explicitly simulating the processes and resources within the airport terminal, as in [18]; or modelling different transport modes (metro, bus, taxi) linked to passenger archetypes (business traveller, holidaymaker, family, etc.), as in [26]. This will enable the selection of a faster ground mobility mode as a mechanism to manage disruptions. Mercury also facilitates the evaluation of the combination of mechanisms (*e.g.* flights waiting for passengers working jointly with a Fast-track to process passengers). Finally, trade-offs regarding passenger metrics and operational costs could be explored.

## VII. ACKNOWLEDGEMENT

This work has been performed as part of the MultiModX project, which has received funding from the SESAR Joint Undertaking under grant agreement No 101114815 under European Union's Horizon Europe research and innovation programme. The opinions expressed herein reflect the authors' views only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

## REFERENCES

[1] European Commission (EC), "Sustainable and smart mobility strategy—putting european transport on track for the future," 2020.

[2] A. Cook, G. Tanner, S. Cristóbal, and M. Zanin, "Passenger-oriented enhanced metrics," in 2nd *SESAR Innovation Days*, 2012.

[3] L. Delgado, G. Gurtner, M. Weiszer, T. Bolic, and A. Cook, "Mercury: an open source platform for the evaluation of air transport mobility," *13th SESAR Innovation Days*, 2023.

[4] Y. Su, K. Xie, H. Wang, Z. Liang, W. A. Chaovalitwongse, and P. M. Pardalos, "Airline disruption management: A review of models and solution methods," *Engineering*, vol. 7, no. 4, pp. 435–447, 2021.

[5] L. Hassan, B. F. Santos, and J. Vink, "Airline disruption management: A literature review and practical challenges," *Computers & Operations Research*, vol. 127, p. 105137, 2021.

[6] M. Santana, J. De La Vega, R. Morabito, and V. Pureza, "The aircraft recovery problem: A systematic literature review," *EURO Journal on Transportation and Logistics*, p. 100117, 2023.

[7] A. Shalaby, L. Li, and E. Diab, "Rail transit disruption management: a comprehensive review of strategies and approaches," *Handbook of public transport research*, pp. 280–313, 2021.

[8] H. Balakrishnan, "Airline disruption management with delay ledgers," in *10th International Conference on Research in Air Transportation (ICRAT)*, June 2022.

[9] A. D'Ariano, M. Pistelli, and D. Pacciarelli, "Aircraft retiming and rerouting in vicinity of airports," *IET Intelligent Transport Systems*, vol. 6, no. 4, pp. 433–443, 2012.

[10] N. Pilon, A. Cook, S. Ruiz, A. Bujor, and L. Castelli, "Improved flexibility and equity for airspace users during demand-capacity imbalance-an introduction to the user-driven prioritisation process," *6th SESAR Innovation Days*, 2016.

[11] J. Evler, M. Lindner, H. Fricke, and M. Schultz, "Integration of turnaround and aircraft recovery to mitigate delay propagation in airline networks," *Computers & Operations Research*, vol. 138, p. 105602, 2022.

[12] Y. Xu, S. Wandelt, and X. Sun, "Immuner: Integrated multimodal mobility under network disruptions," *IEEE Transactions on Intelligent Transportation Systems*, vol. 24, no. 2, pp. 1480–1494, 2023.

[13] F. Sun, H. Liu, and Y. Zhang, "Integrated aircraft and passenger recovery with enhancements in modeling, solution algorithm, and intermodalism," *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 7, pp. 9046–9061, 2021.

[14] C. Baumgartner, J. Kätker, and N. Tura, "Dora–integration of air transport in overall urban and regional mobility information," *Transportation Research Procedia*, vol. 14, pp. 3238–3246, 2016.

[15] A. Marzuoli, E. Boidot, P. Colomar, M. Guerpillon, E. Feron, A. Bayen, and M. Hansen, "Improving disruption management with multimodal collaborative decision-making: A case study of the asiana crash and lessons learned," *IEEE Transactions on Intelligent Transportation Systems*, vol. 17, no. 10, pp. 2699–2717, 2016.

[16] G. Scozzaro, C. Mancel, D. Delahaye, and E. Feron, "An ilp approach for tactical flight rescheduling during airport access mode disruptions," *International Transactions in Operational Research*, vol. 31, no. 3, pp. 1426–1457, 2024.

[17] J. Bueno-González, J. Burrieza-Galán, O. G. Cantú-Ros, C. Livingston, S. Penazzi, C. Buire, A. Marzuoli, and D. Delahaye, "Air-rail timetable synchronisation for seamless multimodal passenger travel: a case study for valencia-lanzarote door-to-door journeys," *Transportation Research Procedia*, vol. 71, pp. 85–92, 2023.

[18] G. Scozzaro, M. M. Mota, D. Delahaye, and C. Mancel, "Simulation-optimisation-based decision support system for managing airport security resources," in *EUROSIM 2023*, 2023.

[19] S. Bouarfa, J. Müller, and H. Blom, "Evaluation of a multi-agent system approach to airline disruption management," *Journal of Air Transport Management*, vol. 71, pp. 108–118, 2018.

[20] G. Gurtner, L. Delgado, and D. Valput, “An agent-based model for air transportation to capture network effects in assessing delay management mechanisms,” *Transportation Research Part C: Emerging Technologies*, vol. 133, p. 103358, 2021.

[21] S. Zaoli, P. Mazzarisi, F. Lillo, L. Delgado, and G. Gurtner, “New centrality and causality metrics assessing air traffic network interactions,” *Journal of Air Transport Management*, vol. 85, 2020.

[22] L. Delgado, A. Cook, E. Zareian, T. Bolic, E. Gregori, and A. Paul, “Challenges of multimodal door-to-door mobility modelling,” in *Proceedings of the 12th SESAR Innovation Days*, December 2022.

[23] L. Delgado, C. Trapote-Barreira, A. Montlaur, T. Bolić, G. Gurtner, and T. Bolic, “Airlines’ network analysis on an air-rail multimodal system,” *Journal of Open Aviation Science*, vol. 1, no. 2, 2023.

[24] Euronews, “Spain has proposed a ban on short-haul flights - but environmental groups aren’t happy,” 2023. [Online]. Available: https://www.euronews.com/green/2023/11/03/spain-has-proposed-a-ban-on-short-haul-flights-but-environmental-groups-arent-happy

[25] Journal officiel Lois et Décrets France, “LOI n° 2021-1104 du 22 août 2021 portant lutte contre le dérèglement climatique et renforcement de la résilience face à ses effets,” 2023, https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000043956924. Accessed on 25/10/2023.

[26] E. Zareian, L. Delgado, A. Cook, E. Gregori, T. Bolic, H. Kadour, A. Correas, and A. Paul, “Modus D4.2 Mobility models description,” SESAR, Tech. Rep., 2022.