

Convective Weather Impact on Airspace Capacity: A Comparison between Permeability and Workload Based Approaches

Gabriele Enea & Tom Reynolds
ATC & Weather Systems Group
MIT Lincoln Laboratory
Lexington, MA, USA
gabriele.enea@ll.mit.edu

Luigi Perrotta¹, Antimo Pontillo²
& Patrizio Ripesi³
¹Long Term & Exploratory Research
²Enhanced Solutions & MBS
³ATM System Evolution & SSP
Enav SpA., Rome, Italy
patrizio.ripesti@enav.it

Christina Young & Martin Durbin
NextGen Modeling & Analysis Division
Federal Aviation Administration (FAA)
Washington, DC, USA
christina.young@faa.gov

Abstract—Convective weather is one of the major aviation hazards impacting air traffic in domains from airports to en-route operations. Convective cells can pose a significant safety hazard due to severe weather phenomena, such as hail, lightning, icing, and turbulence. For this reason, pilots usually tend to avoid convective areas, either planning longer trajectories pre-flight or tactically flying around them. These actions can result in large deviations from optimal routes and imbalances in sector demand-capacity loads in neighboring airspace. These could lead to ripple effects impacting the overall network and causing inefficiencies that need to be tactically managed by the Air Navigation Service Providers (ANSPs). Proactively managing these disruptions and capacity imbalances is crucial to planning and implementing effective Air Traffic Flow and Capacity Management (ATFCM). In this study, we compared two approaches for evaluating airspace capacity under convective weather conditions based on airspace permeability and controller workload. These two methodologies are used primarily for US and European airspace respectively, where the actions allowed to mitigate convective weather impacts are slightly different. For the permeability-based approach, the FAA Traffic Flow Impact (TFI) decision-support tool's underlying model is presented to illustrate the approach. For the workload approach, the results obtained from the SESAR3 Industrial Research Project HARMONIC Solution 382 are presented, showing a new methodology for the sector's workload assessment with the presence of convective areas based on the use of additional ATC tasks. The methods are compared to identify strengths and weaknesses, as well as best practices that can be leveraged from each approach which can help inform future R&D priorities.

Keywords – ATM; Convective weather; Safety; Sector Capacity.

I. INTRODUCTION

Weather was responsible for up to 47% of the total network delays during the summer of 2024 in Europe [1] and up to 43% in the U.S. [2], mainly due to the presence of thunderstorms.

It is well-known that convective weather has a significant impact on both en-route and airport operations [3][4], causing major network disruptions [5]. Since the presence of convective cells poses a safety hazard due to hail, lightning, icing, and turbulence [6], pilots tend to avoid these areas by pre-planning

trajectories away from weather-affected regions or tactically deviating around them. Therefore, there is a key role for ground-based decision support systems to aid traffic managers and airline planners in strategically avoiding weather hazards and to maintain some level of traffic flow through the affected airspace. Tactical weather avoidance strategies can also lead to imbalances between demand and capacity in airspace, with a significant impact on network stability [7]. In particular, while the convection-impacted sectors experience a general reduction in the traffic flow, the adjacent sectors will have an overall increase in the traffic load due to the presence of unplanned weather-avoiding flights. This can result in network instability, which needs to be mitigated by applying specific Air Traffic Flow and Capacity Management (ATFCM) in Europe or Traffic Management Initiatives (TMIs) in the US. In the European network, weather avoidance maneuvers can shift traffic to airspace managed by different ANSPs, while in the US to neighboring ANSPs i.e. NAV CANADA or, more often, to airspace of different Air Route Traffic Control Centers (ARTCCs) which are all managed by the Federal Aviation Administration (FAA), making coordination easier in the US than in Europe.

Different ATFCM strategies employ various approaches and operational methodologies, led by the ANSPs, and coordinated with the EUROCONTROL Network Manager in Europe and by the FAA ATC System Command Center (ATCSCC) in the US. For example, in the US, the Air Traffic Controller (ATCo) in coordination with the pilot, can directly modify the flight trajectory to avoid specific portions of the airspace, such as convective areas. In Europe, it is only the prerogative of the pilot to decide whether and how to avoid convective cells, ultimately coordinating with the ATCo. For this reason, the ATFCM/TMI weather regulations for the Europe and US scenarios are planned based on ATCo workload and airspace sector (what we will call “permeability”) impacts, respectively. This study aims to compare these two different approaches, focusing on the convective weather mitigation problem and airspace capacity estimation.



The paper is organized as follows. In Section II, we describe the Permeability approach used in the United States to translate convective weather forecasts into air traffic management impact in support of planning and implementing TMIs, including a case day. In Section III, we briefly describe the procedures recently introduced in Europe to mitigate convective weather conditions. After that, we present the results obtained from the SESAR3 Industrial Research HARMONIC Solution 382, which investigated a new methodology for evaluating ATC workload under convective weather conditions, based on the use of additional controller tasks. Section IV compares the approaches presented in Sections II and III, discussing the major differences and potential applications. Finally, Section V provides a summary of the findings and proposals for future applications.

II. PERMEABILITY APPROACH

A. Weather Translation Approach

Methods to translate convective weather into air traffic management impacts have focused in the past on sector resources. For example, in [8], Cho presents a task-based workload approach extended to model weather impacts on en-route sector capacity. The relationship between sector capacity and weather blockage is found to be nonlinear and hard to forecast in advance. This approach was extended by Welch in [9] to capture aircraft vertical rate changes and to identify workload-related capacity thresholds.

The approach presented in this section is not focused on weather impacts at a sector-level but on airspace that encompasses multiple sectors. This is done to match more closely the en-route weather-related restrictions (TMIs) used in the United States by the FAA to manage such impacts.

The approach was first developed by MIT Lincoln Laboratory for the FAA Traffic Flow Impact (TFI) tool for en-route airspace [10] and extended for terminal airspace in [11]. A block diagram of the basic algorithm is presented in Figure 1. TFI uses a combination of deterministic and probabilistic weather forecast models of different meteorological variables as inputs. The ensemble set of weather forecasts is mapped to a

metric of airspace blockage called “permeability” where 0% represents complete blockage of the airspace and 100% is completely clear of weather. The permeability metric also considers the route structure over the region of interest to capture the fact that differently-shaped weather systems affect the airspace differently depending on the orientation of the weather relative to the airspace structure, such as its primary traffic flows. TFI calculates permeability for 12 hours into the future at specific regions of en-route airspace that can encompass large portions of an ARTCC. In this way, the calculations are more robust to small variations in the forecasted weather cells’ locations and magnitudes, which are notoriously hard to forecast for small regions over many hours.

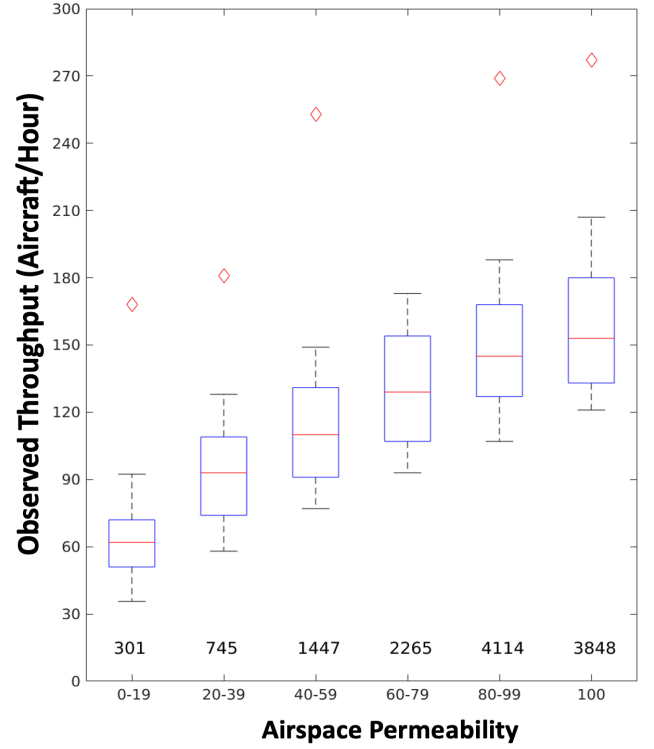


Figure 2. Observed throughput versus airspace permeability for the Jacksonville ARTCC ZJX001 TFI box in the summer of 2022.

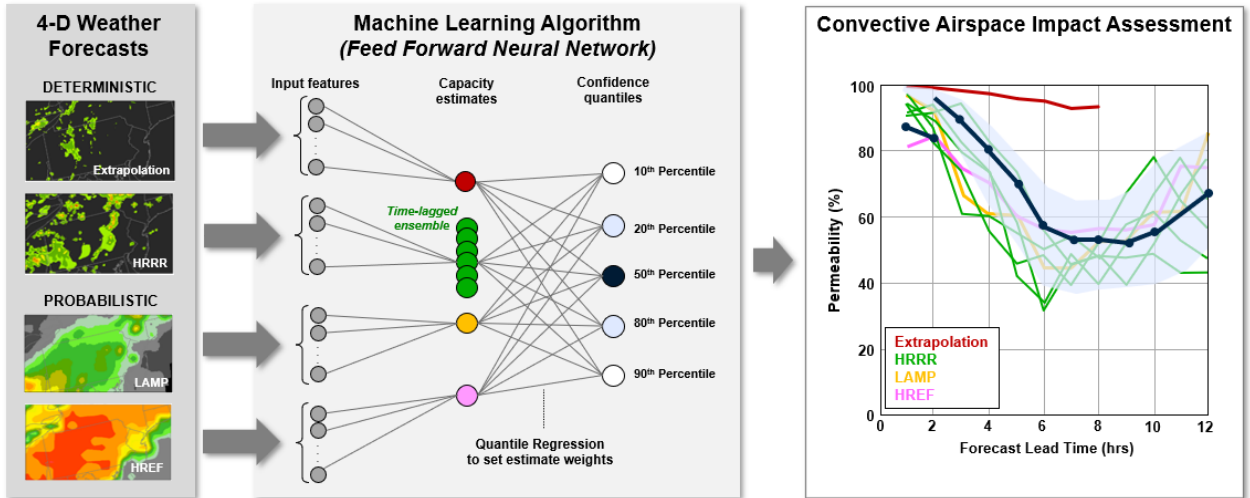


Figure 1. Simplified weather-to-airspace capacity translation process used in the Traffic Flow Impact tool (adapted from [10]).

Weather cells reduce the capacity of an airspace. Therefore, to benchmark the airspace capacity as a function of the weather impacts, the historical observed traffic throughput is correlated to the impact of the Permeability metric discussed above. Figure 2 shows such plots for a region in the Jacksonville ARTCC called ZJX001, visible in Figure 3, for the summer 2022 period. The red line in Figure 2 represents the median observed throughput, the box shows the inter-quartile range and the whiskers show the extent of the outliers.

TFI Permeability is based on the Consolidated Storm Prediction for Aviation (CoSPA) [12] operational prototype radar mosaics. CoSPA weather extrapolations are based on multiple weather inputs such as the High Resolution Rapid Refresh (HRRR) model [13]. These allow CoSPA to produce 1 km grid resolution forecasts updated every 5 minutes for the 0-2 hour time horizon, and 3 km resolution forecasts updated every 15 minutes for 2-12 hour time horizons. The TFI Permeability forecasts are also updated every 15 minutes. Operationally, TFI is used to plan for weather impacts using predicted Permeability to help define Airspace Flow Programs (AFPs). Similar to ATFCM regulations, these programs reduce the demand of flights by setting maximum-allowable flow rates across control lines into the airspace at certain times. To set AFP rates, Traffic Managers can use the predicted Permeability presented by TFI to help define the start, duration and severity of the program for each of the TFI forecasted hours, as illustrated in the case study next.

B. Case Day

To illustrate how the Permeability compares to AFP rates and observed throughput of traffic, a case day from ZJX is presented in this section [14]. The case day of June 21, 2023 presented significant forecasted weather impacts that can be seen in the TFI tool in Figure 3. The top panel shows the weather forecast over time while the cyan boxes show the geographic extent of various TFI regions (ZJX001, 006 & 007).

The colored cells at the bottom show categorical information on the permeability impact of the weather (green=low, yellow=medium and red=high) on different airspace regions (the rows of the table) at different 1 hour time bins out to 12 hours into the future (the columns of the table). These forecasts are updated every 5 minutes in real time. On this day at the time shown (1100Z), it is seen from the top row of the color-coded table that weather was already having medium impacts on region ZJX001 (the middle cyan box), which were forecasted to rise to high impact in 10 and 11 hours time. The right side of the Figure shows a graphical representation of the forecast permeability of that region over the full 12-hour period, including confidence bounds (20th-80th percentiles) to show the range of likely outcomes based on historical analysis of weather forecast performance. This kind of information on impacts of weather on regions of airspace hours into the future is very relevant for strategic air traffic management decision-making. Currently the FAA ATCSCC uses a variety of weather models and tools for strategic planning, of which TFI is just one. TFI does not present a direct translation of permeability into AFP rates. Therefore, the Traffic Managers at the ATCSCC have to use their experience to make that translation. To mitigate the weather impacts shown in Figure 3, on that day the FAA imposed a 10-hour AFP along the control line denoted JX5 (see the white line which approximately covers the superset of regions ZJX001, 006, and 007) with set rates of 90 aircraft/hour from 1200Z-1900Z, and then 110 aircraft/hour for 2000Z-2100Z: see TABLE 1.

Analyzing historical data (from the FAA Wilbur database) of actual traffic throughput, it is seen that during seven of the 10 hours of the program, the observed throughput was higher than the AFP set rates used, as summarized in Table 1. A positive delivery difference means that, for that hour, the observed throughput was higher than the AFP set rate. A negative number means that the throughput was lower than the set rate for that hour such as in hours 13, 20 and 21. A total of

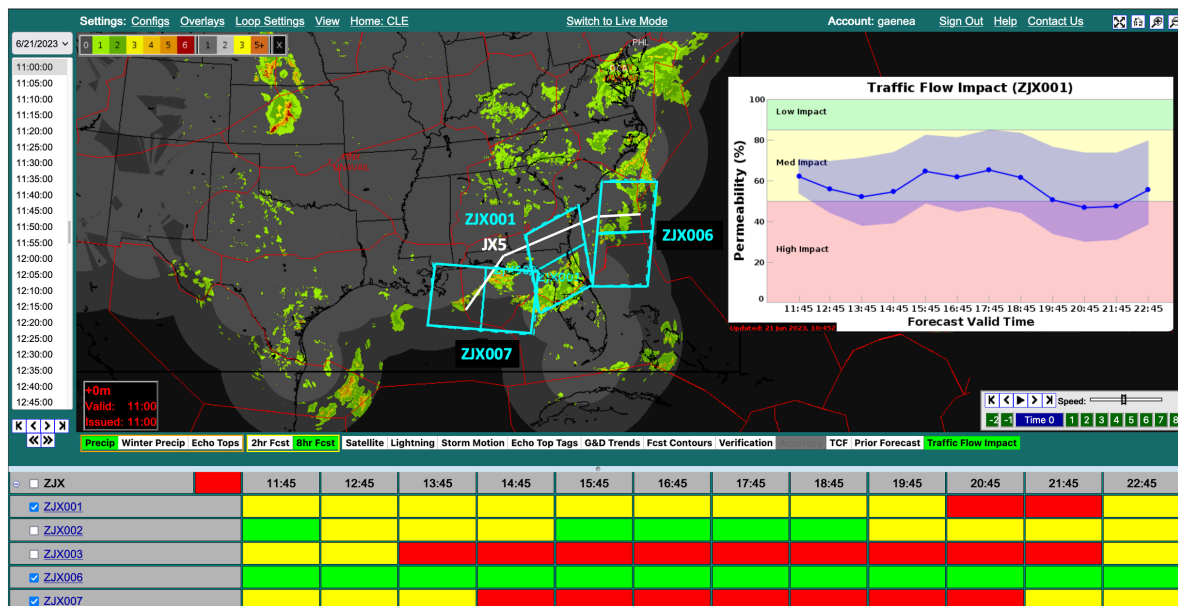


Figure 3. TFI user interface at 1100Z on June 21, 2023.

88 more flights than planned were processed during the JX5 AFP on the case day, suggesting that higher rates could have been set if advanced weather translation technology was available to the ATCSCC Traffic Managers that would directly translate airspace weather impacts to AFP rates. This may have allowed more effective traffic management planning to occur.

TABLE 1. JUNE 21 2023, JX5 PROGRAM SUMMARY & RATE ANALYSIS.

Hour (Zulu)	Observed Traffic Rate (ac/hr)	Actual AFP Rate (ac/hr)	Observed – AFP Difference (ac/hr)	Proposed TFI-Based Rate (ac/hr)	Observed – TFI Difference (ac/hr)
12	108	90	+18	112	-4
13	75	90	-15	112	-37
14	104	90	+14	95	+9
15	105	90	+15	95	+10
16	119	90	+29	107	+12
17	115	90	+25	97	+18
18	95	90	+5	97	-2
19	103	90	+13	97	+6
20	101	110	-9	102	-1
21	103	110	-7	102	+1
Total			+88		+12

As mentioned before, TFI does not directly perform this translation in its current version. But in order to explore if TFI could have been used to inform different AFP flow rates on the case day, the 60th percentile of the permeability for the predicted hour was mapped to achievable throughput values in Figure 2 and used as a proxy for a TFI proposed rate, also shown on the right side in Table 1. This analysis suggests that TFI would have proposed higher rates for the first 8 of the 10 hours of the AFP. For 7 of these 8 hours, the observed throughput was higher than the AFP rate, over the 10 hours only 12 more flights were delivered with the TFI rates than planned (compared to 88 with the AFP rate).

Over the 10 hours the JX5 AFP was in place on the case day, 1,306 flights were delayed with an average delay of 92 minutes, imposing 120,152 total minutes of ground delays on the system. Many of these delays were most likely necessary given the severe weather that was affecting the Florida airspace on the case day. But this analysis suggests that advanced technology might have been used to refine the delay programs to better match what airspace capacity was actually available.

III. WORKLOAD APPROACH

The airspace Permeability approach is based on the aircraft throughput in a given airspace at a given time, where the presence of a convective weather cell (denoted as Cumulonimbus, or CB) is considered as a physical obstacle to flights. By contrast, the Workload approach is based on ATCo workload assessment, considering the time (in minutes) spent performing each required task [15], with airspace capacity determined by the corresponding number of flights. In this perspective, since convective weather conditions can significantly increase the ATCo's workload due to additional tasks related to CB avoidance maneuvers [8], the airspace capacity must be reduced to keep the total workload within the required safety limit [16]. This will be discussed in the

following sections, where we present the recent convective weather mitigation initiatives introduced in Europe and the results obtained from research conducted within the SESAR HARMONIC Solution 382 framework.

A. Convective Weather Mitigation Initiatives in Europe

Maintaining the ATCo's workload within safety limits is a key concern [16] [17], particularly during convective weather conditions, when increased complexity can pose significant safety risks. Convective weather can create hazards like turbulence, icing, and lightning, all of which require air traffic controllers to manage aircraft avoidance requests and maintain separation. This, in turn, leads to increased workload that can be mitigated by the issuance of dedicated ATFCM regulations, reducing the overall airspace demand to match the reduced capacity. Because European airspace consists of many ANSPs, harmonized procedures are needed, given that mitigations applied in one airspace may impact the airspace of neighboring nations. To this end, EUROCONTROL has recently developed a series of initiatives within the framework of the Cross Border Convection Advisory. This collaborative environment, coordinated by EUMETNET, provides the EUROCONTROL Network Manager and participating ANSPs with information about convective weather conditions in European airspace in the form of Cross Border Convection Forecast (CBCF) maps [18]. The CBCF consists of the regular issuance of dedicated maps (see example in Figure 4), issued during the summer season from May to mid-October, which highlight the probability and extent of convective areas through color-coded polygons. Forecasts are published at 0700Z each day of the season by a member of the EUMETNET CBCF module, made up of the German Deutscher Wetterdienst, Meteo France, UK Met Office, and Finnish Meteorological Institute, which rotates weekly. The first issue for the operating day starts the day before operations (D-1), with forecasts running from 0900Z to 2100Z, divided into three-hour blocks, updated at 2200Z for the day of operations (D-0). These forecasts are used by the EUROCONTROL Network Manager, local Air Traffic Management Services, selected airports and airlines, as well as other stakeholders to coordinate the necessary mitigation measures. The latter typically includes calling in stand-by controllers, postponing military exercises, relaxing routing restrictions, and, starting in summer 2025, re-routing aircraft traffic to avoid highly convective weather-impacted areas. This is achieved through ad-hoc coordination with airlines and the issuance of dedicated Route Availability Document (RAD) relaxations, based on different scenarios developed during the pre-tactical phase and applied at D-1 to D0, depending on weather conditions [19].

B. Convective Weather in the HARMONIC Solution 382

The concept of Dynamic Airspace Configuration (DAC) involves organizing, planning, and managing airspace configurations to respond effectively to shifts in traffic demand and unforeseen events, improving the distribution of ATCo's workload.

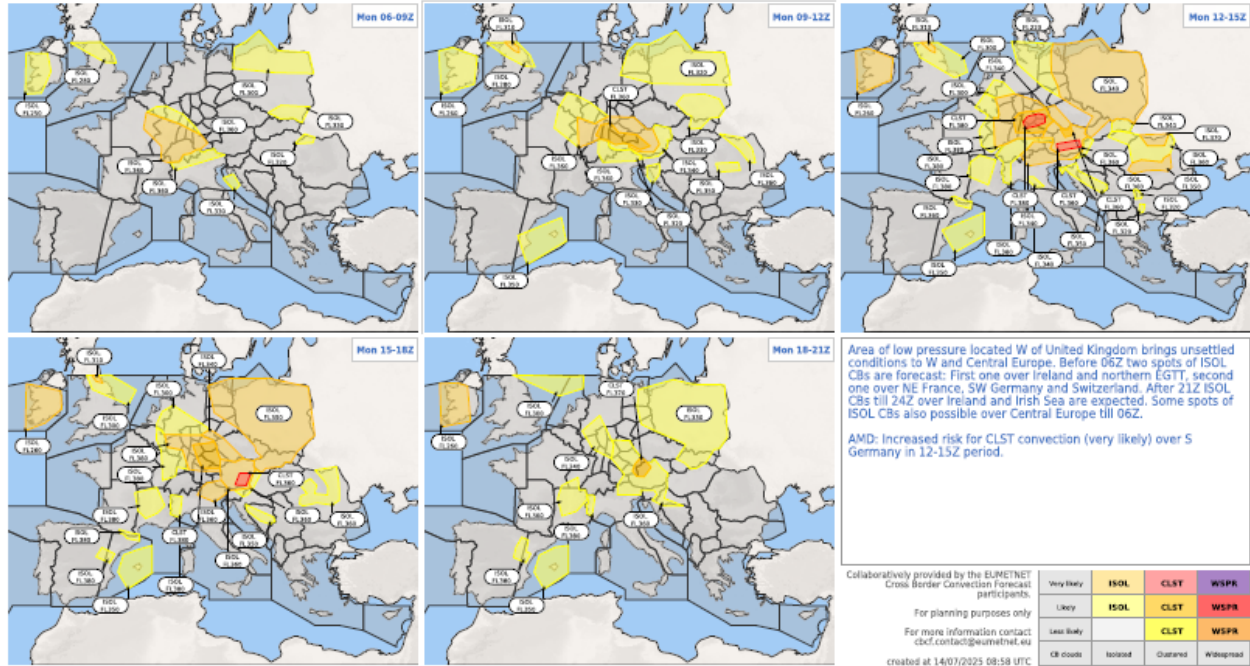


Figure 4. An example of a CBCF map, issued on 13 July 2025 at 2200Z for D-0.

One of the main applications of the DAC concept is the reorganization of airspace sectors in response to real-time traffic conditions. Over the years, several methodologies have been explored to address the DAC problem, including the use of flexible airspace boundaries [20], computational geometries [21], genetic algorithms [22], and an optimization model based on state-task networks [23]. However, despite the significant amount of dedicated research, additional complexities, such as weather conditions and military restrictions, have not been considered. These, instead, represent the scope of the SESAR3 HARMONIC Project, Solution 382.

The solution explores the development of the DAC concept, considering the potential presence of severe weather conditions and/or military area restrictions. These airspace constraints will be managed by the DAC algorithm using dedicated AI/ML techniques to dynamically determine the optimal sector configuration. Since the focus of this paper is on convective weather conditions, we will only discuss that case, but additional details about the HARMONIC Project and the development of the DAC algorithm are available in [24].

As a first step in our project development, we needed to quantify the effect of convective weather regions on ATCo workload and related airspace capacity. Several approaches could be applicable, such as direct measurement of ATCo workload [25], estimation from the analysis of historical flight data [26], and the use of dedicated Fast Time Simulation (FTS) [16]. For our purposes, we used FTS, where the presence of convective areas was modeled as additional ATC tasks. The reference scenario used in the exercise is related to sectors

inside the Milan Area Control Center (LIMM), referred to as Traffic Volumes (TV) in TABLE 2. TV's refer to the portion of regulated airspace as defined in [27]. The meteorological scenarios are selected from the list of the most impactful (in terms of ATFM Delay) weather regulations issued during the summer of 2023, as shown in TABLE 2.

Convective areas related to the summer of 2023 were obtained using data from the single-level hourly ERA5 dataset by applying a composite post-processed analysis [28]. As a measure of the storm intensity, Convective Available Potential Energy (CAPE) areas greater than 150 J Kg^{-1} were considered, with four different intensity levels based on different Convective Rain Rate (CRR) thresholds, ranging from below 0.25 mmh^{-1} (no convection) to greater than 2 mmh^{-1} (high-intensity convection).

TABLE 2. MOST IMPACTFUL DAYS FOR WEATHER REGULATIONS (CBS) IN THE SUMMER OF 2023.

Date	Activation Time	Impacted Traffic Volume	Regulated Flights	ATFM Delay
30/06/2023	05.00 15.00	LIMAWY12	904	9775 min
30/07/2023	16.20 21.40	LIMAWY12	475	4461 min
24/07/2023	13.40 22.30	LIME12	42	6317 min
20/10/2023	08.30 13.31	LIMWC37	323	4459 min
21/10/2023	09.00 19.01	LIMAWY37	900	5417 min

Following the method used for the CBCF maps, convective areas are shown as color-coded polygons within the LIMM airspace. Unlike the CBCF, where convective areas are assessed based on both the intensity and the probability of

occurrence over a three-hour forecast period, since our analysis is based on actual past events, our polygons represent solely the intensity of convective areas evaluated over one hour. Additionally, we empirically set the top of the convection at FL400, justified by the fact that during deep thermodynamic convection conditions, such as in summer, CBs tend to develop up to the tropopause at about FL370. Since clear air turbulence events caused by CBs can still occur above this level, we opted to extend the top of the convective areas up to FL400.

To understand how convection affects air traffic, Figure 5 displays an image of convective polygons and their impact on flight routes. As shown, the main effect of the convective area is to cause flights to deviate horizontally to avoid the zones of highest intensity, leading to longer and more complex paths (planned routes top vs actual routes bottom). This, on one hand, confirms the validity of our post-processing method; on the other hand, it provides valuable input for assessing the impact on ATCo workload.

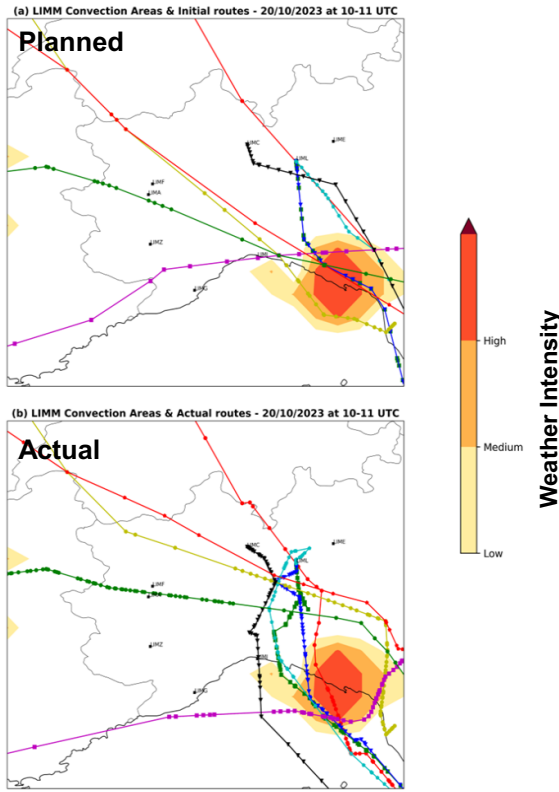


Figure 5. Convective area intensity and flight trajectories, over LIMM on 20 October 2023 at 1000Z-1100Z, for planned (top) and actual (bottom) trajectories.

C. Evaluation of the Impact of Convection on Airspace Capacity based on Fast-Time Simulations

The FTS used to evaluate the impact of convective areas was developed based on the airspace model of Milan ACC, covering a total of nine convective weather scenarios from summer 2023. Airspace capacity was assessed using a regression-based approach, establishing a relationship between traffic flown and the corresponding controller workload, generated by time-based task modelling [29]. This is similar to

sector Monitor Alert Parameters (MAP) values used in the US to monitor sector loads [30].

Under normal operating conditions, when there are no convective weather phenomena, the workload estimated through FTS represents the full range of tasks typically performed by an ATCo to safely and efficiently manage traffic. When convective cells are present, additional complexity arises because pilots may need to request deviations to avoid dangerous weather zones. The FTS models the effect of convective areas by adding an extra task based on the severity of the weather encountered.

The task introduced, referred to as “single instruction of route, heading or speed plus readback,” models the pilot’s request to avoid the area affected by the convective cells and the corresponding ATCo’s readback. The time weight assigned to this task is 9 seconds. The choice of this value is based on empirical data collected during a measurement campaign observing communications between ATCos and pilots where the average duration of a route/speed instruction, including readback, was measured at 9 seconds. This value already incorporates a safety margin to account for the statistical variability observed in instruction durations. In the FTS simulation, this task is implemented by assuming that in CB areas, the medium-intensity zone is nested within the low-intensity one, and similarly, the high-intensity zone is always within the medium-intensity area. Additionally, since convective areas are not entirely covered by zones requiring avoidance, a probability of task application is introduced for each intensity level based on operational feedback.

Based on these considerations, the task is implemented in the FTS model for a flight encountering a convective area of low intensity, adding a task duration of 9 seconds to 50% of the affected flights, to 75% of the affected flights if encountering medium intensity convection, and to 100% of the flights encountering high intensity convection.

These values have been defined empirically, assuming that the avoidance maneuvers requested by pilots to ATC depend on the intensity of the convective area encountered. For low-intensity convection, as in the case of CBs that are not fully developed vertically and/or lasting for less than an hour, we assume that half of the flights involved require one avoidance maneuver, corresponding to a task of 9 seconds applied to 50% of the encounters. Following this principle, for medium- and high-intensity convective areas, we add another 9-second task for 75% and 100% of encounters, respectively.

FTS was performed for each of nine CB scenarios. The analysis focused on LIMM ACC, considering 58 Traffic Volumes (TVs), defined as segments of the airspace associated with an entity within which sector entries and workload are measured. Each TV represents a designated portion of airspace that may be assigned to an ATCo. Each weather scenario was conducted over a 48-hour traffic sample, keeping the shape of the convective polygons fixed throughout the simulation. This approach allowed the simulation to capture the effects of

convective weather on the evolution of demand during the simulation.

For each TV, hourly sector entries and corresponding controller workload were recorded using a 10-minute rolling window. At the end of each simulation, a workload estimate based on sector entries was generated for each TV. The maximum hourly capacity was identified where the regression polynomial curve intersected the Heavy Load Threshold (HLT, which assumes a limit of 70% of a time window used for tasks, equating to 42 minutes in one hour [16]) as shown in Figure 6. If traffic demand was too low or produced few data points on the plot, additional samples were simulated to refine the regression.

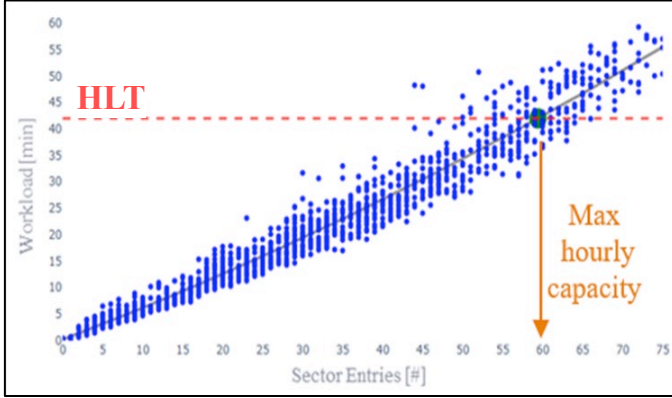


Figure 6. Example of a regression model for capacity evaluation based on workload and sector entries, intersected with a predefined HLT.

The described procedure was repeated for all nine CB scenarios, plus a baseline case without CB, to obtain reference capacities. At the end of the process, hourly capacity values were collected for all Traffic Volumes across the CB scenarios and normalized relative to the reference case, as shown in Figure 7. This figure displays the distribution of relative capacity, calculated as the ratio of capacity in the CB-affected airspace to its baseline, as a function of the CB-induced impact. As observed, relative airspace capacity tends to decrease proportionally with CB/TV values, ranging from 0.98 for a CB/TV interval of 0-10% to 0.65 for a CB/TV of 50-60%. Intuitively, the more convective weather covers the airspace (TV), the lower the capacity. Effects caused by different intensities of convective areas are visible in the whiskers' spread, where, assuming equal total coverage, lower whisker values are linked to high-intensity convection, while higher whisker values correspond to low-intensity convection.

FTS scenarios, task weight choice and final validation of the results, were conducted through dedicated sessions involving ATCos, Flow Manager Positions and Aviation Meteorology experts.

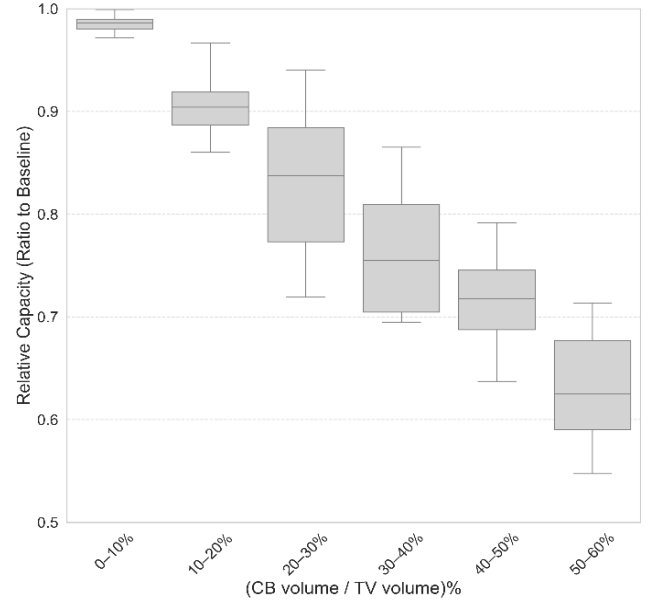


Figure 7. Results of relative capacity as a function of storm coverage.

IV. DISCUSSION

Two approaches to translate convective weather into ATM impacts were presented in this paper: one based on a permeability metric and another based on simulations of controllers' workload. While the TFI permeability approach has been extensively validated through operational prototyping and is part of the tools available to FAA Traffic Managers to deal with weather events, the workload approach is being studied in support of the SESAR 3 HARMONIC Solution 382 project, currently in development. The TFI permeability approach is based on real-time weather forecasts and weather radar data updated every 5 minutes, while the workload simulation uses static weather polygons, corresponding to the one-hour CBs evolution, for several past meteorological scenarios.

Moreover, being integrated into an operational system, the permeability approach can be used in "predictive" mode to support day-of operations to mitigate weather impacts on busy airspaces across the US, but also to look at historical data, as shown in Section II.B. The workload approach, at this stage, can be used to define workload thresholds for different weather impact levels and to look at historical case days.

The results obtained from these two approaches are shown in Figure 2 and Figure 7. Although these two methods use different techniques, comparing their results as a function of the convective area coverage could be useful for analyzing behaviors and similarities. An example comparison for the two analysis cases presented in this paper is shown in Figure 8.

Figure 8 shows the comparison between the results obtained by applying the Permeability and Workload approaches in terms of relative capacity and throughput as a function of the percentage of airspace covered by convective weather. The X axis for the Workload approach corresponds to the CB/TV metric shown in Figure 7, while for the Permeability approach, it corresponds to the opposite of the observed permeability

shown in Figure 2 (i.e., zero in the X axis in Figure 8, represents a permeability of 100% in Figure 2, corresponding to a completely clear day).

The X axis is obtained considering the midpoint of the bin intervals for both datasets, while the Y values have been normalized relative to the median value at permeability of 100% and zero CB/TV for the distributions in both figures (the highest median value in both cases). Therefore, obtaining a measure of the throughput as a percentage of the maximum achieved throughput without weather. This was necessary to fit two data sets with very different values (Figures 2 and 7) into a single plot. The dashed lines are obtained by applying a linear regression analysis to the median points for each dataset.

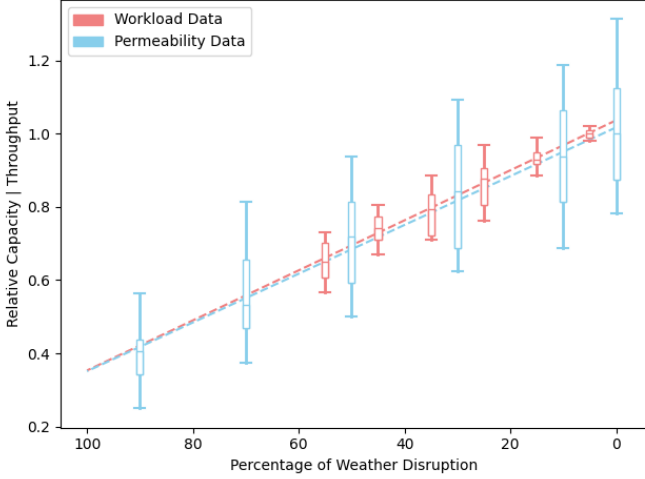


Figure 8. Distribution of the relative airspace capacity with the Workload approach for LIMM (red boxes and line) and throughput with the Permeability approach for ZJX001 (blue boxes and line) versus percentage of weather impacts.

As we can see, regardless of the differences, the results obtained from the two methodologies presented here show very similar behaviors. Even if the boxes' whiskers are significantly different (higher for the Permeability case due to the larger amount of data with respect to that obtained from the FTS for the Workload one), the slopes and intercepts are very similar, resulting in very close airspace capacity-throughput values as a function of the weather impact, despite the very different methodologies and airspaces being used.

V. CONCLUSIONS

Convective weather is a major source of disruptions for air traffic. Accurately translating the weather impact into airspace capacity is critical for managing these disruptions and supporting ANSPs in mitigating their effects. Two methods to perform this translation are presented in this paper, each based on the different operational procedures applied in the U.S. and European airspace. Despite the differences in methodologies and degree of operational maturity, the results obtained from the comparison of the Permeability and Workload approaches show very similar behaviors, resulting in a similar evaluation of the impact induced by the presence of convective weather within the airspace and providing a kind of mutual validation

among the two techniques. The results obtained are thus very encouraging in terms of robustness of the approaches, opening the way to a possible generalization of the methodologies applied to other airspaces and operational scenarios.

The workload assessment method implemented with FTS is routinely applied to predict controller workload on nominal non-weather conditions and define capacity in Italian airspace, with the results validated through operational review. To extend this approach to the European context, considering weather conditions in a broader area, a sufficient number of CB scenarios must be simulated to ensure the predictor's effectiveness. Consequently, a database would need to be populated with data describing the impact of CBs in the relevant areas. In addition, the task-based workload model should be parameterized for each actor, such as the ANSP.

Furthermore, it is worth noting that some complexities may arise when extending the workload-based approach to a wider airspace, such as across Europe, due to the high computational costs of the FTS. While these costs may be acceptable during testing, they could pose a challenge during potential operational deployment of the tool. This problem can be addressed using artificial intelligence/machine learning (AI/ML) techniques for workload estimations applied to a range of different weather, air traffic, and airspace scenarios, computed using FTS. The latter point is the subject of ongoing investigations.

In future research, the developed concept for assessing the impact of convective areas on airspace capacity will be applied to the DAC concept formulation, as planned in the evolution steps of the HARMONIC project. Additionally, we aim to develop an operational tool to evaluate the sector's workload under convective weather conditions, based on the workload methodology presented in this paper. This could be improved by integrating real-time weather forecasts, such as the underlying models used by TFI, providing a best-of-both-worlds solution. Finally, further investigation regarding the permeability and workload methods applied across different weather, airspace, and traffic scenarios should be pursued to validate the robustness and generalizability of the results obtained, as well as to help guide future development opportunities.

ACKNOWLEDGMENTS

This work was conducted as part of the HARMONIC project. This project has received funding from the SESAR Joint Undertaking under grant agreement No 101114675 under the European Union's Horizon Europe research and innovation program. UK participant NATS in Horizon Europe Project HARMONIC receives funding from UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee [grant number 10091990]. This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or SESAR 3 Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them. The authors also thank the Copernicus Climate Database for providing the historical ERA5 reanalysis data. Special thanks also go to Paolo Nasetti, Giorgio Berti,

Luna Babusci, Debora Palombi, Erminio Felicetti, Giuseppe Esposito, Fabio Longo, Federico Del Duca, Giuseppe Di Bitonto, Chiara Mozzetti, and Ramona Santarelli (Enav S.p.a.) for their support during the project development.

The US results were developed with support from the FAA System Analysis and Modeling Division (ANG-B7). The authors would like to thank Mike Matthews (MIT LL) for providing the Permeability data for the analysis.

DISTRIBUTION STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited. This material is based upon work supported by the Federal Aviation Administration under Air Force Contract No. FA8702-15-D-0001 or FA8702-25-D-B002. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Federal Aviation Administration. © 2025 Massachusetts Institute of Technology. Delivered to the U.S. Government with Unlimited Rights, as defined in DFARS Part 252.227-7013 or 7014 (Feb 2014). Notwithstanding any copyright notice, U.S. Government rights in this work are defined by DFARS 252.227-7013 or DFARS 252.227-7014 as detailed above. Use of this work other than as specifically authorized by the U.S. Government may violate any copyrights that exist in this work.

REFERENCES

- [1] EUROCONTROL, “Summer 2024 Performance”, European Aviation Trends, 2024, URL: <https://www.eurocontrol.int/publication/summer-2024-performance>
- [2] Bureau of Transportation Statistics, “Causes of National Airspace System Delays”, 2024, URL: https://www.transtats.bts.gov/OT_Delay/ot_delaycause1.asp?6B2r=1&20=E.
- [3] Enea, G., Reynolds, T., Venuti, J., Polishchuk, T., Polishchuk, V., Lemetti, A., Lau, A., Solzer, J. & Bölle, T., “Comparing Convective Weather Impacts on Air Traffic Management Operations in United States, Canada & Europe”, 34th International Congress of the Aeronautical Science, Florence, Italy, [Link](#), 2024.
- [4] Enea, G., Reynolds, T., Weber, M., Codina, R.D. & Schaefer, D. “Analysis of Weather-Driven Air Traffic Management Challenges for Major US and European Airports”, 14th SESAR Innovation Days, 2024.
- [5] Lau, A., Berling, J., Linke, F., Gollnick, V. & Nachtigall, K., “Large-scale Network Slot Allocation with Dynamic Time Horizons”, 11th USA/Europe Air Traffic Management Research and Development Seminar, 2015.
- [6] Tazarek, M. et al., “Severe Convective Storms Across Europe and the United States”, *Journal of Climate*, Vol 33 (23), pp.10263-10286, 2020.
- [7] Krozel, J., “Survey of Weather Impact Models used in Air Traffic Management”, 10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2010.
- [8] Cho, J. Y. N., Welch, J. D. & Underhill, N. K., “Analytical Workload Model fEstimating En Route Sector Capacity in Convective Weather”, 9th USA/Europe Air Traffic Management Research and Development Seminar, 2011.
- [9] Welch, J. D. Cho, J. Y. N. Underhill, N. K. & DeLaura, R. A., “Sector Workload Model for Benefits Analysis and Convective Weather Capacity Prediction”, 10th USA/Europe Air Traffic Management Research and Development Seminar, 2013.
- [10] Matthews, M.P., Veillette, M.S., Venuti, J.C., DeLaura, R.A. & Kuchar, J.K., “Heterogeneous Convective Weather Forecast Translation into Airspace Permeability with Prediction Intervals”, *Journal of Air Transportation*, 24 (2), pp.41-54, 2016.
- [11] Matthews, M.P., DeLaura, R. & Venuti, J., “Strategic Forecasts of TRACON Airspace Capacity During Convective Weather Impacts”, 17th AIAA Aviation Technology, Integration, and Operations Conference, 2017.
- [12] Evans, J.E., Weber, M.E. & Moser, W.R., “Integrating Advanced Weather Forecast Technologies into Air Traffic Management Decision Support”, *Lincoln Laboratory Journal*, 16 (1), p.81, 2006.
- [13] Dowell, D.C., et. al, “The High-Resolution Rapid Refresh (HRRR): An hourly updating convection-allowing forecast model. Part I: Motivation and system description”, *Weather and Forecasting*, 37(8), pp.1371-1395, 2022.
- [14] Enea, G. & Reynolds, T.G., “Analysis Methodology of Weather-Driven Airspace Flow Programs”, 25th Integrated Communications, Navigation and Surveillance Conference, Brussels, Belgium, 2025.
- [15] Welch, J.D., Andrews, J.W. & Martin, B.D., “Macroscopic Workload Model for Estimating En Route Sector Capacity”, NASA Ames Research Center: Moffer Field, CA, USA, 2011.
- [16] EUROCONTROL, “Pessimistic Sector Capacity Estimation,” 2019, URL: <https://www.eurocontrol.int/node/9925>.
- [17] Brooker, P., “Control Workload, Airspace Capacity and Future Systems,” *Human Factors and Aerospace Safety*, Vol. 3 (1), pp.1-23, 2003.
- [18] Jurković, J. & Šoljan, V., “European Collaborative Convection Forecast for Air Traffic Management - Experiences from Croatian MET Provider,” *EMS Annual Meeting 2024*, Barcelona, Spain, 1–6 Sep 2024.
- [19] EUROCONTROL, “NMOC Capacity and Weather-based operations,” 2025, URL: https://www.eurocontrol.int/sites/default/files/2025-03/eurocontrol-flight-dispatcher-days-2025-nmoc-capacity-and-weather-based-operations_0.pdf.
- [20] Kopardekar, P. Bilimoria, K. & Sridhar, B., “Initial Concepts for Dynamic Airspace Configuration”, 7th AIAA ATIO Conference, p. 7763, 2007.
- [21] Mitchell, J. Sabhnani, G. Hoffman, R. Krozel, J. & Yousefi, A., “Dynamic Airspace Configuration Management Based on Computational Geometry Techniques”, *AIAA Guidance, Navigation and Control Conference and Exhibit*, p. 7225, 2008.
- [22] Sergeeva, M. Delahaye, D. Mancel, C. & Vidosavljevic, A. “Dynamic Airspace Configuration by Genetic Algorithm”, *Journal of Traffic and Transportation*, Vol. 4(3), pp.300-314, 2017.
- [23] Lema-Esposto, M. Amaro-Carmona, M. Valle-Fernández, N. Iglesias-Martínez, E. & Fabio-Bracero, A. “Optimal Dynamic Airspace Configuration (DAC) Based on State-Task Networks (STN)”, 11th SESAR Innovation Days, pp.7-9, 2021.
- [24] Criscuolo, P. Perrotta, L. Di Bitonto, G. & Grani, G. “Enhanced Dynamic Airspace Configuration Algorithm,” 14th SESAR Innovation Days, 2024.
- [25] Suarez, N. Lopez, P. Puntero, E. & Rodriguez, S. “Quantifying Air Traffic Controller Mental Workload,” 5th SESAR Innovation Days, 2014.
- [26] Rhoda, D.A. Kocab, E.A. & Pawlak, M.L. “Aircraft Encounters with Convective Weather in En Route vs. Terminal Airspace above Memphis Tennessee,” 10th Conference on Aviation, Range, and Aerospace Meteorology, American Meteorological Soc., 2002.
- [27] EUROCONTROL, “Improved Configuration Optimiser Technical Documentation,” 2006, URL: <https://www.eurocontrol.int/publication/improved-configuration-optimiser-technical-documentation>.
- [28] Tazarek, M. Kendzierski, S. & Pilguj, N. , “Hazardous Weather Affecting European Airports: Climatological Estimates of Situations with Limited Visibility, Thunderstorm, Low-Level Wind Shear and Snowfall from ERA5”, *Weather and Climate Extremes*, Vol. 28, 2020.
- [29] EUROCONTROL, “Adaptation of Workload Model by Optimisation Algorithms and Sector Capacity Assessment,” 2005.
- [30] FAA, Section 8, Monitor Alert Parameter, URL: https://www.faa.gov/air-traffic/publications/atpubs/foa_html/chap18_section_9.html, 2021.

