7th International Conference on Research in Air Transportation, ICRAT'16

ATM Performance analysis in Madrid ACC sectors considering optimal aircraft trajectories

Guillermo Orenga Imaz
CRIDA ATM R+D Research Centre
Universidad Carlos III Madrid (UC3M)
gorenga@e-crida.enaire.es

Manuel Soler
Department of Bioeng. and Aerospace Engineering
Universidad Carlos III de Madrid (UC3M)
Leganés (Madrid), Spain

***Abstract*—In the future Air Traffic Management (ATM) system, the trajectory becomes the fundamental element of a new set of operating procedures collectively referred to as Trajectory-Based Operations (TBO). This has encouraged a renewed interest for the application of trajectory optimization techniques in commercial aviation, resulting in the so-called continuous operations. They have shown significant benefits in terms of fuel savings and CO_2 emissions. Unfortunately, the real implementation of continuous operations is in turn still far to be possible. Its implementation must be also tested and compared against other ATM performance indicators such as safety and capacity. Therefore, the main contribution of this paper is to provide a preliminary analysis on how an operational concept allowing continuous operations might affect the ATM performance at a network level. Different state-of-the art indicators will be used to measure ATM performance in terms of flight efficiency, environment, safety, and capacity. For the sake of illustration, a case study based on Madrid's ACC is considered. Current operational scenario (based on Flight plans) and an envisioned scenario allowing continuous operations (based on 4D optimised trajectories) are compared in three different days (with high, medium, and low traffic).**

***Index Terms*—4D Trajectory Optimization, Continuous Operations, ATM performance.**

I. Introduction

Nowadays, approximately 30000 flight plans are produced in Europe every day. Aircraft are constrained to fly through predefined routes both vertically and laterally, resulting in flight plans usually far from optimal, eventually leading to an increase in operational cost and environmental impact [1, Section 3.5]. In the envisioned Air Traffic Management (ATM) system to be built around SESAR, the trajectory becomes the fundamental element of a new set of operating procedures collectively referred to as Trajectory-Based Operations (TBO) [2]. Indeed, derived from the above mentioned TBO concept, new operational concepts are demanded to reduce the cost and environmental impact per flight as much as practicable. These operational concepts are known as continuous operations, resulting from the optimisation of trajectories either during climb, cruise or descent phases.[1]

Extensive research related to the potential benefits derived from the application of continuous operations to individual flights has been recently done both in simulation scenarios and real-trials.

For the former, see for instance [3], [4], [5], and [6]. As illustration, Soler et al. in [4] provides both qualitative and quantitative measure of the potential benefits of continuous operations with respect to current procedures for a single flight. In [4] results showed that continuous profiles can achieve around 11% (short-haul flights) and 6% (medium-haul flights), i.e., between 220 and 380 [kg], of fuel savings and associated CO_2 emissions[2] of 700 and 1200 [Kg] when compared to current operations.

Regarding real trials, refer for instance to Project AIRE (Atlantic Interoperability initiative to Reduce Emissions) [8]. Within its framework, more than 1000 trial flights were performed with a global savings of 400 tons of CO_2 emissions (roughly 0.4 tons per flight).

All these results clearly illustrate that the implementation of continuous operation could bring benefits that are somehow aligned with some the main goals pursued by SESAR, i.e., 8-14 [min] gain per flight on average; 300-500 [kg] reduction in fuel per flight on average; 945-1575 [kg] reduction of CO_2 emissions per flight on average by 2020.[3] Unfortunately, the real implementation of continuous operations is in turn still far to be possible. Its implementation must be also tested in multi-aircraft scenarios at a traffic network level and compared against other key performance areas such as safety and capacity.

Indeed, SESAR is looking for new effective methodologies and tools for micro and macro modelling of performance in ATM, capable of capturing the interdependencies between different Key Performance Areas (KPAs) of safety, capacity, cost effectiveness, and environment. Any new solution and/or operational change must be tested against these KPAs.

As a result, the main contribution of the present paper is to provide a preliminary analysis on how an operational concept allowing continuous operations might affect the ATM

[1] They are referred continuous climbs, continuous cruise, and continuous descent operations, respectively.

[2] a direct relation between fuel burnt and CO_2 emissions (around 3.15 kg of CO_2 per kg of fuel burnt) [7]

[3] please refer to www.sesar.ju

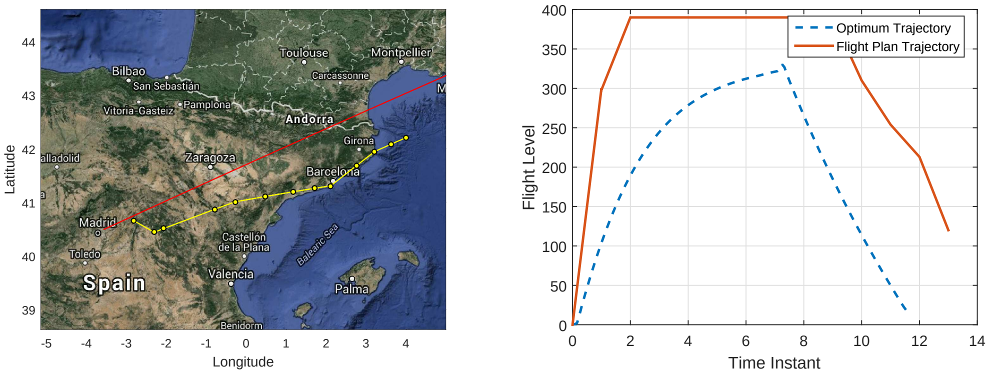

Figure 1. Route Comparison and Vertical profile.

performance at network level. A prior study on conflict pattern analysis under the consideration of continuous operations in Europe was presented in [9]. In this paper, we go beyond utilizing different state of the art indicators to assess the performance of the ATM in areas such as safety, capacity, environment, and cost effectiveness.

Standard metrics on flight efficiency and environment are based on over-distances flown with respect to the great-circle distance. These assume constant speed and altitude profiles and the above mentioned direct relation between fuel burnt and CO_2. Notice however that an optimal profile does not typically present constant speed nor constant altitude profiles. Moreover, the great circle is not necessarily the optimum path if wind is considered (even though for the sake of simplicity is not used in this paper). Therefore, metrics based on fuel consumption and flight times (using dynamic models) seem more appropriate rather than deviations in terms of distances from the Great Circle path. Some experimental tools such as Impact [10] and AEM [11] are available via Eurocontrol to quantify fuel burnt, emissions, and noise based on 4D trajectories.

Regarding performance indicators for operational efficiency, the trend and the studies developed in [12] are followed. Optimal control theory [13] will be used to optimise aircraft trajectories. Fuel burnt, NO_x and CO_2 emissions computed with AEM [11] will be used as flight efficiency and environment indicators.

State of art indicators for safety and capacity will be also used, i.e., number of conflicts (aggregated and de-aggregated per Sector); complexity metrics (based on ATC workload metrics developed in [14]); separation available in conflicts (distance between two conflictive aircraft at their nearest point compared to the loss of separation minima); maximum occupancy of sectors; entry counts; over-capacities; etc. The reader is referred to [15] for more insight on these metrics.

For the sake of illustration, three different scenarios are built as case study. They correspond to dates in which a high, a medium and a low density of traffic has been encountered in Madrid ACC. Real flight plans are compared against optimised flight plans. RAMS PLUS 5.0 [16], [17] is used to simulate Madrid ACC sectorization and simulate the different scenarios. Indicators of efficiency, environment, safety, and capacity are presented to illustrate how ATM performance (based in this case on Madrid ACC's sectors) could be affected by the implementation of continuous operations.

The paper is structured as follows. In Section II, environmental and flight efficiency aspects are analysed. In particular, continuous operations concept and optimal control is exposed. In Section III, safety and capacity issues are tackled. Later in Section V the case study is described. Section V is devoted to expose the obtained results. Some conclusions and future directions of research are drawn in Section VI.

II. Environment and Flight Efficiency Indicators

Environmental and flight efficiency metrics are based on the comparison (fuel burnt and gaseous emissions) of current profiles (based on FP) and optimised profiles (based on continuous operations under the hypothesis of a both lateral and vertical free-flight).

Figure 1 presents a flight with destination LEMD. The optimum path is displayed in red while the actual trajectory is shown in yellow.[4] Vertical profiles are also depicted.

A. *Flight Planning*

A flight plan is an aviation term defined by the International Civil Aviation Organization (ICAO) as [18].:

> *Specified information provided to air traffic services units, relative to an intended flight or portion of a flight of an aircraft.*

A flight plan is prepared on the ground. It gives information on route, flight levels, speeds, times, and fuel for different flight phases, alternative airports, and other relevant data for the flight, so that the aircraft properly receives support from ATS in order to execute safe operations. Furthermore, due to ATC supervision requirements, aircraft flying in controlled airspace must follow predetermined routes.

A route is a description of the path followed by an aircraft when flying between two airports. A complete route often uses

[4] Note that flight plan information based on the actual trajectory is only available within the Spanish airspace.

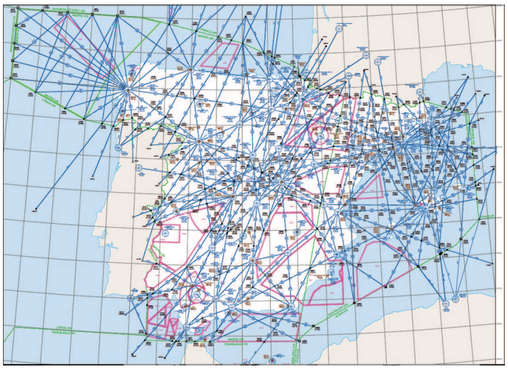

Figure 2. En-route upper navigation chart (Old chart, not for operational use). Source: AIP Enaire.

several airways. Additionally, there exist special tracks known as ocean tracks, which are used across some oceans. Free flight is also permitted in some areas over the oceans.

The routes of the complete network are referred to as ATS routes. The complete route of an aircraft flying between two airports can be divided in three main parts: origin, en-route, and destination. Within the framework of this paper, we restrict ourselves to analyse the en-route volumes of airspace. The en-route phase is defined by a series of waypoints and airways. An en-route upper navigation chart for the Iberian Peninsula is given in Figure 2, illustrating the different ATS routes (in blue), the limited areas (in pink), and the UIR regions (in green). Current flight plans follow this network of ATS routes. In some continental airspaces, there might be areas of lateral free routing.

B. Flight Planning and the environment

An effective flight plan can reduce fuel costs, time-based costs, overflight costs, and lost revenue from payload that cannot be carried, simply by choosing efficient routes and altitudes, speed, and the optimal amount of departure fuel. Optimizing the flight plan to reduce fuel not only saves money, but indirectly reduces the environmental fingerprint of air transportation. An overview on aviation environmental impact is given in [19]. Emissions from aviation account for approximately 3% of total green house effect gases in Europe [20, Section 2.3] and 3.5% of CO_2 man made European emissions [1]. In 1999 the United Nations Intergovernmental Panel on Climate Change (IPCC) forecasted, as aviation was expected to grow to meet increasing demand, that its share of global man made CO_2 emissions would increase to around 3% to 5% in 2050 (in 1999 it was estimated to be 2%) [21].

Reducing thus the aviation environmental fingerprint is peremptory. The reduction in fuel consumption and CO_2 emissions will require contributions from new technologies in aircraft design (engines, airframe materials, and aerodynamics), alternative fuels (bio fuels), improved Air Traffic Management (ATM), and operational efficiency (mission and trajectory management). Indeed, EUROCONTROL estimates that approximately 6% of the burnt fuel and CO_2 emissions related to aviation in Europe is due to inefficiencies in the ATM European system [1, Section 3.5].

C. Continuous operations

Continuous operations result to the solution of a flight planning problem, which can be regarded as a trajectory optimization problem. The trajectory optimization problem can be studied as an optimal control problem applied to individual flights, in other words, applied to the microscale level and without considering the potential network effects (mesoscale).

1) Optimal Control Problem: The goal of optimal control theory is to determine the control input that will cause a dynamical system (typically characterized by a set of differential-algebraic equations) to be steered from an initial state configuration to a final one, satisfying a set of path constraints, and at the same time optimize some performance criterion.

Problem 1 (***Optimal Control Problem***)**.**

$$\begin{aligned}
&\min\ J(t, x(t), u(t), p) = E(t_f, x(t_f)) + \int_{t_0}^{t_f} L(x(t), u(t), p)dt;\\
&\textit{subject to:}\\
&\dot{x}(t) = f(x(t), u(t), p),\ \textit{dynamic equations;}\\
&0 = g(x(t), u(t), p),\ \textit{algebraic equations;}\\
&x(t_0) = x_0,\ \textit{initial boundary conditions;}\\
&\psi(x(t_f)) = 0,\ \textit{terminal boundary conditions;}\\
&\phi_l \leq \phi[x(t), u(t), p] \leq \phi_u,\ \textit{path constraints.}
\end{aligned} \tag{OCP}$$

Variable $t \in [t_0, t_f] \subset \mathbb{R}$ represents time and $p \in \mathbb{R}^{n_p}$ is a vector of parameters. Notice that the initial time t_0 is fixed and the final time t_f might be fixed or left undetermined. $x(t) : [t_0, t_f] \mapsto \mathbb{R}^{n_x}$ represents the state variables. $u(t) : [t_0, t_f] \mapsto \mathbb{R}^{n_u}$ represents the control functions, also referred to as control inputs, assumed to be measurable. The objective function $J : [t_0, t_f] \times \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}$ is given in Bolza form. It is expressed as the sum of the Mayer term $E(t_f, x(t_f))$ and the Lagrange term $\int_{t_0}^{t_f} L(x(t), u(t), p)dt$. Functions $E : [t_0, t_f] \times \mathbb{R}^{n_x} \to \mathbb{R}$ and $L : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}$ are assumed to be twice differentiable. The system is a DAE system in which the right hand side function of the differential set of equations $f : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}^{n_x}$ is assumed to be piecewise Lipschitz continuous, and the derivative of the algebraic right hand side function $g : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}^{n_z}$ with respect to z is assumed to be regular. $x_0 \in \mathbb{R}^{n_x}$ represents the vector of initial conditions given at the initial time t_0 and the function $\psi : \mathbb{R}^{n_x} \to \mathbb{R}^{n_q}$ provides the terminal conditions at the final time and it is assumed to be twice differentiable. The system must satisfy algebraic path constraints given by the function $\phi : \mathbb{R}^{n_x} \times \mathbb{R}^{n_u} \times \mathbb{R}^{n_p} \to \mathbb{R}^{n_\phi}$ with lower bound $\phi_l \in \mathbb{R}^{n_\phi}$ and upper bound $\phi_u \in \mathbb{R}^{n_\phi}$. Function ϕ is assumed to be twice differentiable.

Soler et al. present in [22] a thorough optimal control framework for the statement and resolution of commercial aircraft four-dimensional flight-planning problems. The reader is referred there for details. In what follows we briefly summarise the solution approach followed:

In this article a Hermite-Simpson collocation method [23], [24] will be employed. Thus, the continuous optimal control problem is transcribed into a NLP problem [25]. For the NLP problem to be solved, the NLP solver IPOPT (Interior Point Optimizer) will be used. The mathematical details of IPOPT algorithm can be found in [26]. Source and binary files can be found at COIN-OR (www.coin-or.org).

As for aircraft performance model, we use BADA 3.11 [27]. It considers a 3 degree of freedom dynamic model that describes the point variable-mass motion of the aircraft over a spherical Earth model. Wind is disregarded in the preliminary case study for simplicity purposes.

D. Flight Efficiency and Environment Metrics

Metrics for flight efficiency should include fuel burnt and gaseous emissions. Fuel consumption and emissions are calculated using Eurocontrol's Advanced Emission Model (AEM).

$$(\%Increase_{Fuel}) = \left(\left(\frac{Fuel_{Opt}}{Fuel_{Fp}}\right) - 1\right)\% \tag{1}$$

$$(\%Increase_{NO_x}) = \left(\left(\frac{NO_{x,Opt}}{NO_{x,Fp}}\right) - 1\right)\% \tag{2}$$

$$(\%Increase_{CO_2}) = \left(\left(\frac{CO_{2,Opt}}{CO_{2,Fp}}\right) - 1\right)\% \tag{3}$$

III. Safety and Capacity

A. Safety

There is a wide variety of metrics are available to measure the safety of the airspace [15]. The indicators proposed to measure safety are the increase in number of conflicts, the available separation in conflict and the duration of conflict. These are as follows:

$$(\%Increase_{N.Conflicts}) = \left(\left(\frac{C_{Opt}}{C_{Fp}}\right) - 1\right)\%, \tag{4}$$

where C_{Opt} and C_{Fp} correspond to the number of conflicts in optimum and flight plan trajectories respectively.

$$(\%Increase_{Time}) = \left(\left(\frac{t_{Opt}}{t_{Fp}}\right) - 1\right)\%, \tag{5}$$

where t_{Opt} and t_{Fp} correspond to the duration of conflicts in optimum and flight plan trajectories respectively.

$$(\%AvailableSeparation) = \left(\left(\frac{Min_{dist}}{Max_{sep}}\right) - 1\right)\% \tag{6}$$

The available separation is the ratio of the minimum distance between the two conflictive aircraft Min_{dist} throughout the conflict and the maximum separation available Max_{sep} which corresponds to the loss of separation minima (typically 5 NM en-route).

B. Capacity

A wide variety of metrics may be used to characterize the capacity of a sector of an ATM Network [15], [28]. The metrics used to account for capacity are sector entries as well as maximum sector occupancies during operation. The maximum sector occupancy refers to the largest number of aircraft that occurs throughout the whole operation. In order to compare the occupancy for both types of trajectories the increase in maximum occupancy may be computed as follows:

$$(\%Increase_{Max.Occ}) = \left(\left(\frac{max[Occ_{Opt}]}{max[Occ_{Fp}]}\right) - 1\right)\% \tag{7}$$

Furthermore, travelled distance and flight time within a sector also used.

$$(\%Increase_{D_{Travelled}}) = \left(\left(\frac{D_{Opt}}{D_{Fp}}\right) - 1\right)\%; \tag{8}$$

$$(\%Increase_{t_{Flight}}) = \left(\left(\frac{t_{Opt}}{t_{Fp}}\right) - 1\right)\%. \tag{9}$$

Another method used to measure ATC Capacity is to calculate the Air traffic controller workload resulting from the operation of the different scenarios proposed [28]. In order to do so MWM (Multiple Resources Workload Model) is the tool used [14]. The increase in workload when comparing both trajectories is:

$$(\%Increase_{WL}) = \left(\left(\frac{WL_{Opt}}{WL_{Fp}}\right) - 1\right)\%, \tag{10}$$

where WL stands for Workload. The methodological approach for the calculation of WL is later described in Section IV-D.

IV. Case Study

A. Scenario definition

Three different scenarios are proposed. They correspond to days with a different traffic density, high, medium, and low, respectively. Information regarding the number of flights is presented in Table I. For each of the scenarios both types of trajectories (Optimum trajectories and Flight Plan trajectories) are studied. The purpose of studying three different days of traffic is to analyse the impact of Optimum trajectories with the variation of number of aircraft.

Table I
Traffic Days

Traffic	Number of Aircraft
High	3074
Medium	2732
Low	2209

Figure 3 shows two snapshots with all optimum and flight plan lateral routes in the low traffic scenario. Notice that for the flight plans, only information within Madrid ACC sectors is available. A significative difference on flight paths is remarkable at a first glance. Figure 4 shows altitude profiles

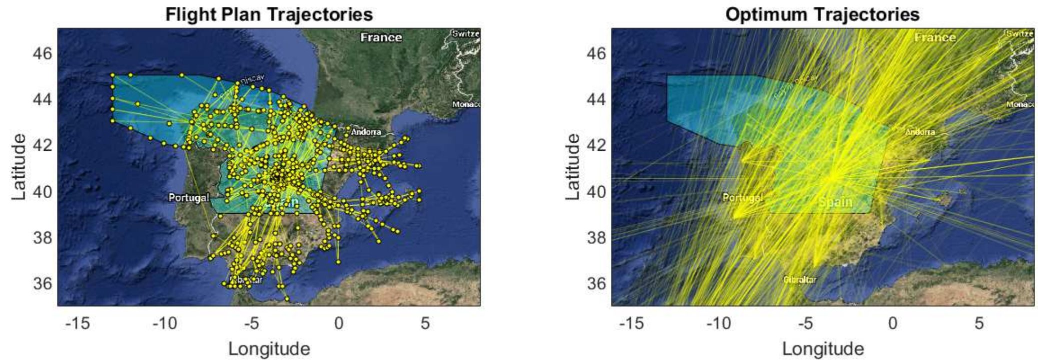

Figure 3. Low Traffic Scenario: Flight PLan Trajectory [left] & Optimum Trajectories [Right]

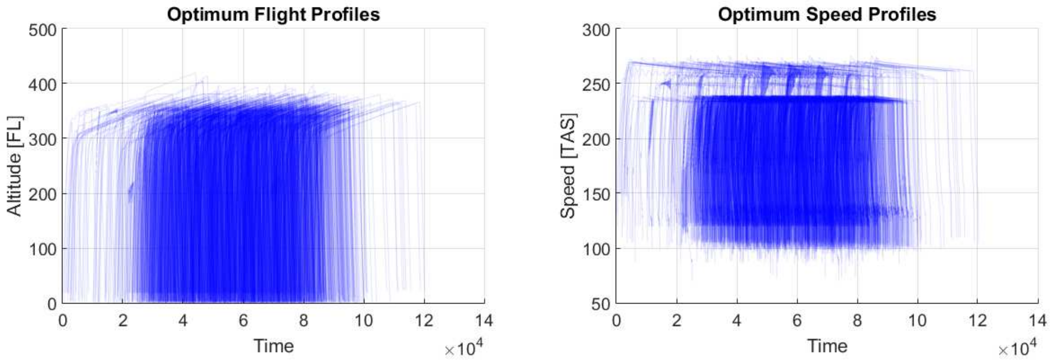

Figure 4. Low Traffic Scenario: Vertical Profiles [Left] & Speed Profile [Right] for Optimum Trajectories

and speed profiles for the set of optimized trajectories again in the Low Traffic Scenario. In this case the characteristic behaviour of optimal vertical profiles is also noticeable, i.e., a continuously increasing altitude profile during cruise followed by a sharp descent and a slightly decreasing speed profile during cruise (optimal speed decreases as fuel is being burnt). Please, refer to [4] for more insight on optimal vertical profiles.

B. FP data

Flight Plan data are retrieved from CRIDA A.I.E databases.

C. RAMS

RAMS PLUS 5.0 is the tool used to model and simulate the scenarios proposed. Flight plan trajectories were built using waypoints and Flight Level. Modelling continuous trajectories is a complex task. RAMS 5.0 Plus can not simulate fully continuous operations. The optimum trajectory has to be divided into waypoints (given by latitude & longitude) and Flight Level. Enough number of points need to be used to maintain the essence of continuous operations. However, as the number of points used to build the trajectory increases so does the computational time in RAMS. Consequently, the track was divided into 11 "Optimum trajectory waypoints".

To analyse conflicts, and the events within the scenario a sectorisation is required. For the sake of simplicity a constant sectorization is used. 9 sectors are open in Madrid Route 1 and 8 sectors are open in Madrid Route 2. The analysis focuses on the events taking place during en-route operation, and therefore, other sectors were ignored. A criteria of 1000 ft in vertical height and 5 nautical miles in horizontal distance was established as minimum criteria for a conflict to be considered.

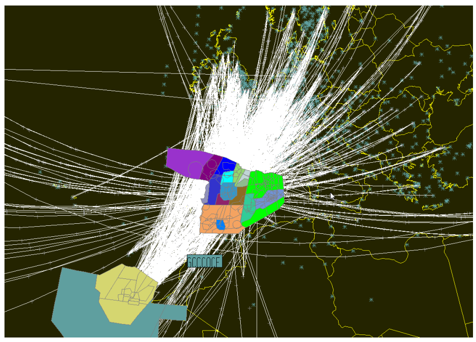

Figure 5. RAMS Optimum Trajectory Scenario

D. Workload Calculation

Workload calculation is done with the use of MWM (Multiple Resources Workload Model). The MWM algorithm starts from an initial state defined by the set of ATCo actions required to address a control event. From this state, the algorithm identifies the required cognitive channels using the available automation features and the time at which the cognition is required to be used. This information is used to construct an interference matrix. The resolution of this matrix leads to the estimation of the demanded resources required to address a control event [14]. A threshold of 50000 units of workload is set as the maximum value for workload. If the total amount of workload during the simulation rises above 50000 it would mean that traffic controllers are overloaded. Workload is calculated for each of the sectors operated in the simulation.

V. Results and ATM Performance Analysis

Three scenarios with two operational concepts for each of the scenarios results in a large volume of results. For the sake of simplicity and brevity, detailed results will be presented only for LECMSAN; the most occidental sector of Madrid ACC. Aggregated results for the whole Madrid ACC will be also presented.

A. Safety Indicators

1) Aggregated results in Madrid ACC: Table II presents aggregated results for the total number of conflicts as indicator of safety. Optimum trajectories lead to an increase in the number of total conflicts. The smallest increase is observed in the medium traffic scenario.

Table II
Overall Conflict Results

	Total Number of Conflicts		
	Flight Plan	Optimum T.	Increase
HIGH	227	578	155%
MEDIUM	138	245	78%
LOW	84	178	112%

2) Detailed results for LECMSAN: Table III shows a summary of the number of conflicts for sector LECMSAN in the three different days of traffic. The total number of conflicts decreases with traffic. However, the highest traffic day shows the best result regarding optimum trajectories. There is 72% less conflicts than when following flight plan routes.

Table III
Conflicts LECMSAN

SECTOR	Conflicts - HIGH TRAFFIC		
LECMSAN	Optimum T.	Flight Plan	Increase
	8	29	-72%
	Conflicts - MEDIUM TRAFFIC		
	Optimum T.	Flight Plan	Increase
	6	1	500%
	Conflicts - LOW TRAFFIC		
	Optimum T.	Flight Plan	Increase
	3	0	300%

Figure 6 shows the approximate time in hours when the conflicts take place. The bar charts represent the three different days.

Table IV summarises both the average available separation and average duration of conflict. Conflicts taking place due to Optimum trajectories occur at an average available separation of 65%. This means that conflicts taking place occur at an average distance of 3.25 [NM] (65% of the loss of separation minima). On the other hand conflicts that arise as a consequence of Flight Plan routes happen at an average of 41% available separation, in average 2.05 [NM]. Therefore, conflicts for Optimum trajectories are in average; shorter in duration, and take place at a larger distance between aircraft.

Table IV
High Traffic - Average Available separation & Average Conflict Duration within LECMSAN

	Optimum T.	Flight Plan	% Increase
Available Separation	65%	41%	59%
Conflict Duration	51.6 s	83.5 s	-38%

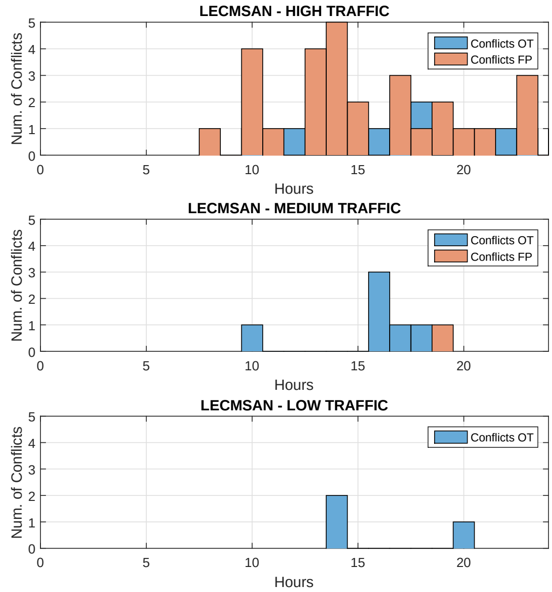

Figure 6. Trajectory Comparison: Number of Conflicts per Sector

B. Capacity Indicators

1) Aggregated results in Madrid ACC: Table V displays the aggregated results for the total summation of the maximum occupancies. This is the result of adding the maximum number of occupancy for all the sectors, for the three different days. Optimum trajectories result in a higher occupancy, however the trend seen is that as traffic increases the difference in results between the two types of tracks is smaller.

Table V
Overall Occupancy Results

	Sum of Maximum Occupancies		
	Flight Plan	Optimum T.	Increase
HIGH	211	262	24%
MEDIUM	176	233	32%
LOW	157	209	33%

2) Detailed results for LECMSAN: Table VI shows the maximum occupancies obtained in LECMSAN during the three days of traffic. The behaviour is similar to the number of conflicts. For the high traffic day there is a maximum of 22 aircraft at the same time within the sector while only a maximum of 10 for aircraft flying the optimum route. This implies a reduction of 129%. The behaviour in optimum tracks for the other two days is similar. Maximum occupancies are 9 and 10 for medium and low respectively.

Table VI
MAXIMUM OCCUPANCIES - LECMSAN

Sector	FP Trajectory	OT	Increase
LECMSAN	Maximum Occupancy - HIGH TRAFFIC		
	22	10	-120%
	Maximum Occupancy - MEDIUM TRAFFIC		
	7	9	22%
	Maximum Occupancy - LOW TRAFFIC		
	6	10	40%

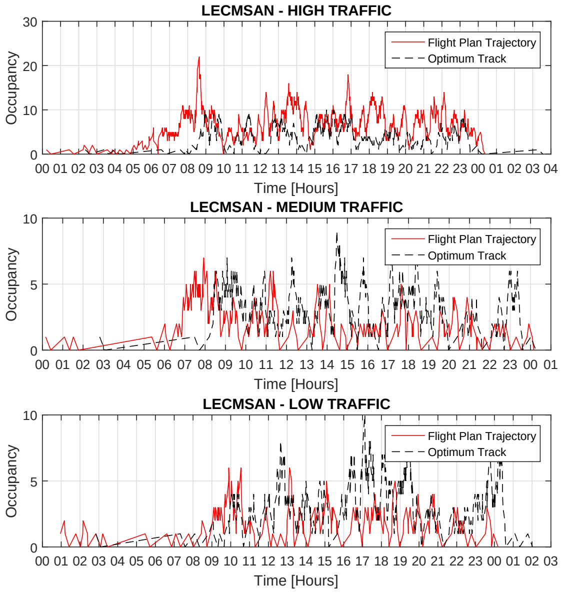

Figure 7. Trajectory Comparison: Sector Entries

Figure 7 shows the entries and exits in the studied sector during the simulation.

C. Environment Indicators

The development of results in this section shows an aggregated view of the three scenarios.

1) Aggregated Efficiency Results: Efficiency metrics for the three different scenarios proposed are displayed in table VII. Positive percentages indicate benefits in Flight Plan trajectory and negative percentages indicate savings in consumption and reduction in emissions when flying an Optimum trajectory. These percentages have been computed for coincidental aircraft [5] that fly within Madrid ACC.

D. Workload

Table VIII collects the results for the total workload of the the three days proposed. The total workload for each of the days never rises above the threshold of 50000 for Flight Plan trajectories. For Optimum trajectories this limit is surpassed in the high and medium traffic scenario, but not in the low traffic scenario. Despite this fact, the workload that results from flying Optimum routes is 56% higher that for Flight plan tracks.

E. Discussion

Although focusing on a single sector, results can be generalised to other sectors on Madrid ACCs. It has been shown that as traffic increases sectors become more crowded and their maximum occupancies increases. In addition, increase in traffic leads to an increase in the absolute number of conflicts. The results on Table III show that the highest number of conflicts takes place for the largest volume of traffic and for Flight Plan routes. Although the overall number of conflicts is larger for Optimum trajectories, the average duration of this conflicts is shorter and they occur at a larger distance than for those generated as a result of the other type of route.

Workload follows the same pattern. As traffic and the total number of conflicts decrease, so does the workload. In Low volume of traffic, Optimum trajectories lead to a higher workload than Flight Plan tracks but are still below the limit. Results shown Table VII show that fuel consumption and emissions decrease for medium and high traffic days. On the other hand for low traffic, flying an optimum route results in an increase of 36% in fuel consumption. This behaviour is due to considering only the part of the track within ACC airspace and would not hold if considering the complete trajectory.

VI. CONCLUSIONS AND FUTURE WORK

In conclusion, workload analysis results, indicate that impact on ATCo workload for Optimum Trajectory operation falls within limits for a low traffic day. Although the value is larger than for flight plan trajectories, it is still below the threshold. However, when looking at fuel consumption and gaseous emission, the best behaviour is obtained for days with a higher traffic demand. Saving 60% to 70% in fuel consumption translates to 15000-20000 saved tons of fuel per day. If a balance of ATCo workload can be achieved, large savings in fuel and emissions may be achieved.

On going work includes analysis of delays as an indicator of capacity (based for instance in the over capacities within the sectors and thus potential regulations), analysis of types of resolution advisories within RAMS, analysis of flows as an indicator of complexity, analysis of ATM cost based on, e.g., the increase/reduction of ATCs needed to safely handle such patterns of traffic.

Future work might include the consideration of wind, the optimisation of trajectories based on minimum climate impact

[5] Same aircraft flying the two types of routes needs to be within Madrid ACC for both types of routes. If it only exists for one, aircraft is not considered.

Table VII
AGGREGATED EFFICIENCY METRICS

	% $Dist$	% $Increase_{Fuel}$	% $Increase_{NO_x}$	% $Increase_{CO_2}$
LOW TRAFFIC	13%	36%	53%	36%
MEDIUM TRAFFIC	-20%	-62%	-63%	-62%
HIGH TRAFFIC	-7%	-58%	-71%	-58%

Table VIII
OVERALL WORKLOAD RESULTS

	Workload		
	Flight Plan	**Optimum T.**	**Increase**
HIGH	42217.66	69522.16	65%
MEDIUM	30233.23	54476.5	80%
LOW	21425.1	33467.81	56%

(and considering contrails effects), and the extension of the scenario to a European level.

REFERENCES

[1] Eurocontrol, Performance Review Comission, "Performance review report an assessment of air traffic management in europe during the calendar year 2011: Eurocontrol PRR 2011," Eurocontrol, Tech. Rep., May 2012. http://www.eurocontrol.int/prc [Retrieved 01/09/2012].
[2] SESAR Consortium, "The ATM Target Concept, SESAR Definition Phase Milestone Deliverable 3," September 2007.
[3] S. Shresta, D. Neskovic, and S. Williams, "Analysis of continuous descent benefits and impacts during daytime operations," in *8th USA/Europe Air Traffic Management Research and Development Seminar (ATM2009), Napa, CA*, 2009.
[4] M. Soler, D. Zapata, A. Olivares, and E. Staffetti, "Framework for aircraft 4D trajectory planning towards an efficient air traffic management," *Journal of Aircraft*, vol. 49, no. 1, pp. 341–348, 2012.
[5] L. Jin, Y. Cao, and D. Sun, "Investigation of potential fuel savings due to continuous-descent approach," *Journal of Aircraft*, vol. 50, no. 3, pp. 807–816, 2013.
[6] R. Dalmau and X. Prats, "How much fuel and time can be saved in a perfect flight trajectory?" in *International Conference on Research in Air Transportation (ICRAT)*, 2014.
[7] IATA, "IATA Carbon Offset Program," *IATA Carbon Offset Factsheet*, no. January, 2014.
[8] European Comission, the FAA and the project AIRE, "Atlantic Interoperability Initiative to Reduce Emission (AIRE). Summary results 2010/2011," SESAR Joint Undertaking, Tech. Rep., 2012.
[9] S. Ruiz and M. Soler, "Conflict pattern analysis under the consideration of optimal trajectories in the european atm."
[10] I. Eurocontrol, "An Integrated Aircraft Noise and Emissions Modelling Platform IMPACT," *IMPACT*, 2014.
[11] F. Jelinek, I. Crook, and M. N. Vo, "Advanced Emission Model (AEM3) Validation Report," *EEC Report EEC/SEE/2004/004*, 2005.
[12] E. Calvo, J. M. Cordero, L. D. Alto, J. López, and M. Vilaplana, "A New Method to Validate the Route Extension Metric against Fuel Efficiency," *Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015) A*, 2015.
[13] J. T. Betts, *Practical Methods for Optimal Control and Estimation using Nonlinear Programming*. Advances in Design and Control. Society for Industrial and Applied Mathematics, 2010.
[14] Suarez, N;Lopez,, P; Puntero, E;Rodriguez, S, "Quantifying Air Traffic Controller Mental Workload," *Fourth SESAR Innovation Days*, no. November, pp. 1–6, 2014.
[15] Eurocontrol, "Performance Review Report 2014," no. May, pp. 1–124, 2015.
[16] G.-t.-g. A. T. M. F.-t. Simulator, *RAMS Plus User Manual*, 2013, no. December.
[17] ISA Software, *RAMS Plus Data Manual*, 2013, no. December.
[18] International Civil Aviation Organization (ICAO), "Procedures for air navigation services. Rules of the air and air traffic services," ICAO Doc 4444-RAC/501, Tech. Rep., 13th Edtion. 1996. http://www.gcaa.com.gh/extweb/images/stories/ais/icaodoc4444.pdf [Retrieved 01/08/2012].
[19] D. Lee, D. Fahey, P. Forster, P. Newton, R. Wit, L. Lim, B. Owen, and R. Sausen, "Aviation and global climate change in the 21st century," *Atmospheric Environment*, vol. 43, no. 22-23, pp. 3520–3537, 2009.
[20] European Environment Agency (EEA), "Laying the foundations for greener transport. TERM 2011: transport indicators tracking progress towards environmental targets in Europe." tec. rep., 2011. http://www.eea.europa.eu/publications [Retrieved 01/09/2012].
[21] J. Penner, "Aviation and the global atmosphere: a special report of IPCC working groups I and III in collaboration with the scientific assessment panel to the Montreal protocol on substances that deplete the ozone layer," International Panel of Climate Change (IPCC), Tech. Rep., 1999.
[22] M. Soler, A. Olivares, and E. Staffetti, "Multiphase optimal control framework for commercial aircraft four-dimensional flight-planning problems," *Journal of Aircraft*, vol. 52, no. 1, pp. 274–286, 2015.
[23] C. R. Hargraves and S. W. Paris, "Direct trajectory optimization using nonlinear programming and collocation," *Journal of Guidance, Control and Dynamics*, vol. 10, no. 4, pp. 338–342, July-August 1987.
[24] O. von Stryk, "Numerical solution of optimal control problems by direct collocation," in *Optimal control - calculus of variations, optimal control theory and numerical methods*, ser. International Series of Numerical Mathematics, R. Bulirsch, A. Miele, and J. Stoer, Eds. Birkhäuser, 1993, vol. 111, pp. 129–143.
[25] J. Nocedal and S. Wright, *Numerical Optimization*. Springer Verlag, 1999.
[26] A. Wächter and L. Biegler, "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming," *Mathematical Programming*, vol. 106, no. 1, pp. 25–57, 2006.
[27] A. Nuic, *User Manual for the base of Aircraft Data (BADA) Revision 3.6*, Eurocontrol Experimental Center, 2005.
[28] X. Fron, "ATM performance review in Europe," *2nd Air Traffic Management Seminar*, no. December, 1998.

AUTHORS BIOGRAPHIES

Guillermo Orenga HOLDS A BACHELORS DEGREE IN AEROSPACE ENGINEERING BY UNIVERSIDAD CARLOS III DE MADRID (UC3M), SPAIN. CURRENTLY HE IS STUDENT FOR THE MSC IN AERONAUTICAL ENGINEERING AT UNIVERSIDAD CARLOS III. SINCE 2015 HE IS A RESEARCHER AT CRIDA (ATM R& D REFERENCE CENTRE LINKED TO THE SPANISH ANSP, ENAIRE).

Manuel Soler PHD AEROSPACE ENGINEERING; ASSISTANT PROF. AT UC3M, WHERE HE LEADS THE AIR NAVIGATION AND CONTROL RESEARCH LINE. HE TEACHES UNDERGRADUATE AND GRADUATE COURSES IN AIR NAVIGATION, FLIGHT MECHANICS AND CONTROL, AND AIR TRANSPORT. HE HAS BEEN A VISITING SCHOLAR AT ETH ZURICH, AND UC BERKELEY. HIS RESEARCH INTERESTS FOCUS ON OPTIMAL CONTROL, STOCHASTIC HYBRID SYSTEMS, AND TRAJECTORY OPTIMISATION IN ATM. HE HAS PARTICIPATED IN SEVERAL RESEARCH PROJECTS (E.G., CLEAN-SKY POTRA) AND HE IS PRINCIPAL INVESTIGATOR OF SESAR H2020 TBO-MET PROJECT, OPTMET PROJECT (FUNDED BY THE SPANISH NATIONAL SCIENCE PROGRAM), AND CONSULTANCY PROJECTS WITH ORGANISATIONS RELATED TO AVIATION AND ATM DOMAIN (BOEING, INNAXIS, CRIDA/ENAIRE). HE HAS PUBLISHED HIS WORK IN SEVERAL JCR JOURNALS AND PARTICIPATED IN ATM RELATED CONFERENCES (E.G., SIDS, ICRAT, ATM SEMINAR). DR. SOLER WAS RECOGNIZED WITH THE SESAR YOUNG SCIENTIST AWARD 2013. HE IS CURRENTLY SUPERVISING 2 PHD STUDENTS (1 CO-FUNDED BY SESAR). DETAILED VITAE INFORMATION CAN BE FOUND WWW.AEROSPACEENGINEERING.ES