ENRI Int. Workshop on ATM/CNS. Tokyo, Japan. (EIWAC 2017)

[EN-A-048] ATM Performance Analysis considering Minimum Climatology Impact Trajectories

Javier García-Heras*, Manuel Soler*, Guillermo Puelles*,
Marcos Sanz¶
*Escuela Politécnica, Area of Aerospace Engineering, Universidad Carlos III de Madrid, Leganés, Madrid, 28911, Spain
Email: javier.garcia-heras@uc3m.es, masolera@ing.uc3m.es, and 100303906@alumnos.uc3m.es
¶Centro de Referencia de Investigación, Desarrollo e Innovación ATM–CRIDA A.I.E, Madrid, 28022, Spain
Email: msbravo@e-crida.enaire.es

***Abstract*—Global warming represents a major problem for human being life as it is known today. Nations are more aware of that issue and are settled contingency measurements to reduce the called greenhouse gas emission, known as the source of global warming. Initially, CO_2 was considered as the key agent, later also NO_x, but recent studies shows that persistent contrails has a non-negligible impact in global warming. We present a study were the ATM performances (fuel consumption, conflicts, number of movements, flight time) are study. To achieve this, four scenarios have been design and simulated with TAAM (software that model the aerospace and traffic). The scenarios is a low traffic day where horizontal profile is computed as the orthodromic route between each origin and destination, common in all scenarios. However, in the vertical profiles each scenario was computed to fly: the Reference Flight Level, the Aircraft Ceiling, the Minimum Climate Impact Flight Level or the Optimal vertical profile.**

I. Introduction

Worldwide aviation and the associated greenhouse gas emissions have received significant attention over the last years. Different studies project that the greenhouse gas emission from the aviation sector will increase by 60% and 300% by 2030 and 2050 [1], respectively. The share of emitted CO_2 in the global total is also expected to become more important, from 2% in 1999 to 3-5% in 2050 [2]. In terms of anthropogenic radiative forcing, an estimate from the United Kingdom (UK) Royal Commission of Environmental Pollution (RCEP) suggests that the aviation sector will be responsible for 6% of the global total by 2050 [3].

The climate change impact of aircraft operations comes from multiple sources, with CO_2 the most known one. Aviation induced NOx also tends to increase tropospheric ozone and reduce methane. However, the increase in radiative forcing associated with ozone is largely offset by methane reduction, resulting in a relatively small net positive NOx impact compared to the CO_2 one. Another important source of aviation-induced climate change is the formation of contrails, which are line-shaped clouds composed of ice particles and formed in the wake of jet aircraft at high altitude where the ambient temperature is very low.

Contrails evaporate quickly if the ambient air is dry, but can persist (see Figure 1) if the ambient air is humid enough. Like natural high clouds, persistent contrails reduce the outgoing terrestrial radiation more than they reflect solar radiation, resulting in warming of the Earth's surface. Quantifying the climate impact of persistent contrails has attracted considerable research interests. Although consensus has yet to be achieved, the general conclusion is that the magnitude of contrail climate impact is non-negligible compared to that of CO_2. Accounting for the formation of persistent contrails, therefore, is paramount to mitigating aviation induced climate impact.

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) [4]. This has encouraged a renewed interest for the application of optimised trajectories that are claimed to be environmentally friendly. They have shown significant benefits in terms of fuel savings and CO_2 emissions. Moreover, most of the studies tackling optimised trajectories focused either on a single trajectory or arrival/approach scenarios, serve [5] and [6] as example where optimal trajectories are analyzed. Also, [7] studied Continuous Climb Operations (CCOs) to improve maximum range operations. However they do not take into account contrail related effects.

Other authors studied in [8] algorithms to calculate wind-optimal trajectories in cruise phase of flight while regions where persistent contrails formation are avoided. In [9] studied different methods to model in 4D the persistent contrail formation and applied to a multi-objective trajectory optimization software to be used as an offline/online strategic flight trajectory planning. Besides, Soler et al. in [10] studied the 4D trajectory problem in a contrail sensitive environment, they minimize the overall flying cost including fuel consumption, CO_2 emissions, passenger travel time and persistent contrail formation.

Given ATM Complexity, a system wide vision is demanded to account for other Key Performance Areas (instead of focusing on the environmental impact of one single trajectory), i.e., safety (measured for instance based on number conflicts/ATC Workload in a given traffic scenario), capacity (measured for instance based on accumulated delay), and ATM service provision cost. This is studied as an example in[11] where Madrid ACC performance indicators such as: efficiency, environment, safety and capacity are presented including a comparison between conventional trajectories and optimal trajectories in terms of fuel consumption. Eurocontrol in [12] investigates the potential environmental impact of several ATM options to avoid the areas where it is most likely to produce contrails using RAMS Plus ATM simulator [13].

Figure 1. Persistent contrail real example

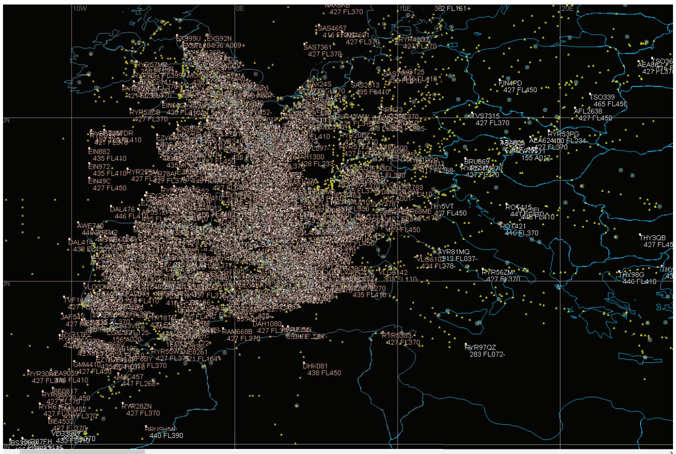


Figure 2. European aerospace in TAAM

The main contribution of this paper is to perform an ATM performances study in a real low day traffic (taking all traffic overflying Spain) and real atmospheric data. Making use of Total Airspace and Airport Modeler (TAAM) software, four scenarios have been compared: optimal, ceiling, environmentally friendly and Reference Flight Level (RFL) trajectories. In the first two, individual trajectories are computed minimising the final mass, in the third optimising total cost including contrails and fuel, and the final one reflects the flight plan trajectory (according current operational paradigm). Each of those scenarios is simulated in TAAM considering the sectorization in Spain, see as an example Figure 2. Different key performance indicators are extracted in order to compare the overall ATM performance.

The paper is structured as follows: the methodology is presented in Section II. The case study is shown in Section III where the used scenarios are presented. In Section IV the simulation results are shown. Finally, some conclusions are drawn in Section V.

II. Methodology

The activities involved to develop the present paper can be grouped in four: scenarios trajectories computation, TAAM simulations, results acquisition, and results analysis, see Figure 3.

The trajectory calculation and the simulation in TAAM have been computed by applying a three-degrees of freedom model with the subsequent aircraft dynamics based on BADA for the different aircraft general data [14].

In the first activities the contrail formation have been developed following the Appleman-Schmidt criterion [15]. The meteorological data needed to fulfil this criterion have been obtained thanks to NOAA [16]. In the Minimum climate impact scenario the different emission associated to the trajectories have been developed with the software AEM Kernel, a software developed and certified for its use by EUROCONTROL [17]. For the Optimal Trajectory scenario, aircraft trajectories have been developed using the Ipopt Solver under the AMPL environment [18].

Later, the four scenarios of traffic individually have been simulated using TAAM software, which stands for Total Airspace and Airport Modeler. TAAM is a Jeppesen software to model airspace and traffic, and also the impact of changes to infrastructure, operations and schedules can be studied [19].

Finally, ATM performance indicators such as: fuel consumption, number of movement per ATC sector, number of conflicts in each ATC sectors, and flight duration, are collected in all the scenarios previously simulated on TAAM to perform later a comparison among them.

III. Case Study

In order to undertake the methodology defined in the previous section, different scenario selections had to be done. In this case, the main decisions to be made were those of chosen the time at which this scope happens, the set of trajectories to be used and the set of different profiles for each fight to be compared.

Only flights that have part of its radar track (or its whole track) inside the Madrid ACC have been selected for the chosen day. The total amount of unique flights extends up to 1869 flights. Note that this is a low traffic scenario because there are usually more than 5000 flights overflying Spanish airspace

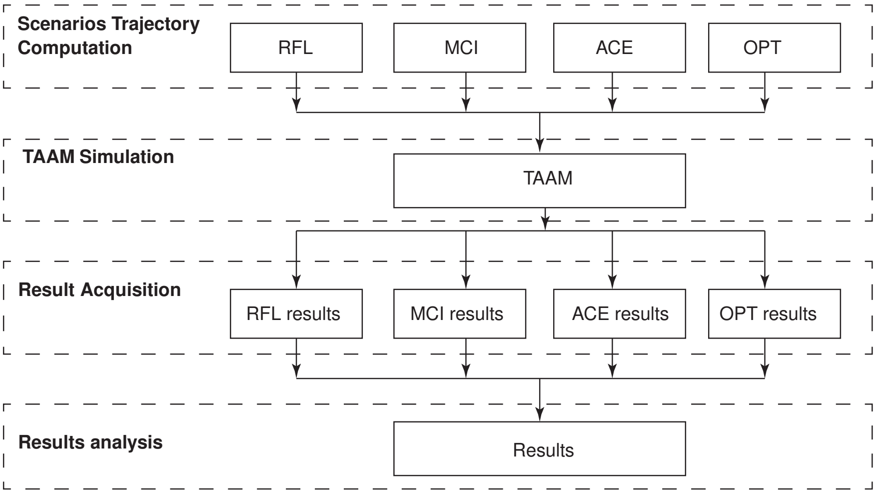


Figure 3. Methodology flow diagram

in a day. The posible FL used by the different scenarios are from FL250 to FL450. The analyzed scenarios are named as follows: Reference Flight Level (RFL), Minimum Climate Impact (MCI), Aircraft Ceiling (ACE), and Optimal Trajectory (OPT).

In the **Reference Flight Level (RFL)** scenario the trajectories are computed with the reference flight level from the flight plan and use it as cruise flight level.

In the **Minimum Climate Impact (MCI)** the trajectories are computed with the cruise flight levels that procure less climatic impact, this is the one that minimize cost from Equation 1.

$$Cost = C_{fuelBurn} + C_{cont} \quad (1)$$

where:

- $C_{fuelBurn}$ is the fuel consumption cost. It is computed as denotes Equation 2. Although not every aircraft uses the same fuel, for the sake of simplicity, kerosene will be the selected fuel for this study. Therefore, the fuel cost (C_{fuel}) is estimate as $1.30048 \frac{\$}{kg_{fuel}}$ [20]; $(m_{final} - m_{initial})$ is the aircraft fuel consumption.

$$C_{fuelBurn} = (m_{final} - m_{initial}) \cdot C_{fuel} \quad (2)$$

- C_{cont} is the contrail emissions cost. It is calculated with the GWP index, which is time horizon dependent. The final cost (in terms of money) of the contrails emissions are computed as it is shown in Equation 3.

$$C_{cont} = GWP_{cont} \cdot C_{unitary-CO_2} \cdot \eta \quad (3)$$

where:

  - $C_{unitary-CO_2}$ is the unitary cost of CO_2 per kilogram of fuel consumed with a value of $0.11 \frac{\$}{kg}$ [21];
  - η is considered the nominal fuel flow for the whole flight, see Equation 4.

$$\eta = \frac{m_{final} - m_{initial}}{t_{final} - t_{initial}} \quad (4)$$

  - GWP_{cont} is the GWP adjusted because GWP values are only valid if the flight is performed always in the regions of contrails persistence. GWP_{cont} is computed as in Equation 5. Where: GWP is equal to 0.74 since 20 years of time horizon has been considered [22], and AF is the adjust factor with a value of 0.15 because it is the middle value of its range of values [0.1–0.2].

$$GWP_{cont} = \frac{GWP}{AF} \quad (5)$$

In the horizontal profile, orthodromic route between origin and destination has been computed in all trajectories. The **Aircraft Ceiling (ACE)** scenario is made by all aircraft flying the minimum fuel consumption cruise flight level.

And the **Optimal Trajectory (OPT)** is the scenario that contains the optimal vertical trajectories in terms of fuel consumption, those will have a Continuous Climb Operations (CCO) in climb and cruise phase of flight and a Continuous Descent Approach (CDA) in the approximation phase, see [23].

The four scenarios are inserted into the TAAM software to simulate them and analyze the ATM performance indicators: Total fuel consumption, and number of movements, and conflicts per ATC sector. For the purpose of posting an example Figure 4 and Figure 5 were illustrated. In Figure 4 we can observe that the minimum climate impact has the lower FL, this is because contrails appear at high altitudes - where aircraft use to fly. Also, RFL is lower than the ceiling FL, this could be imposed for operational reason because aircraft are interested in flying the closest possible to the ceiling FL where lest fuel is burn. Cruise Ground Speed (GS) are very similar in all defined scenarios as can be shown in Figure 5.

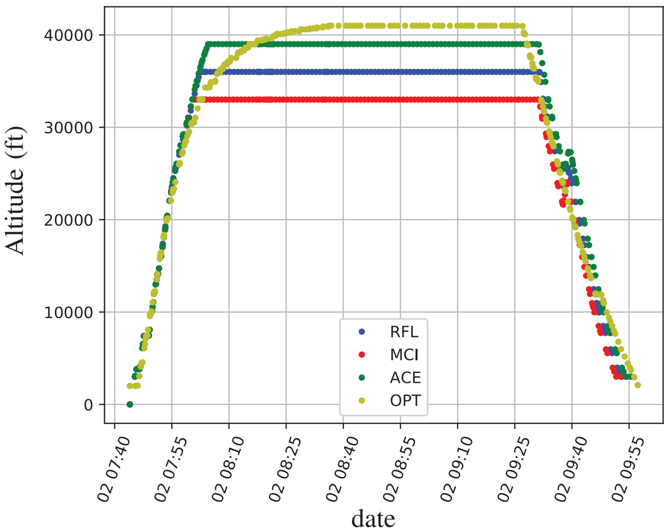


Figure 4. Vertical profile for a representative aircraft

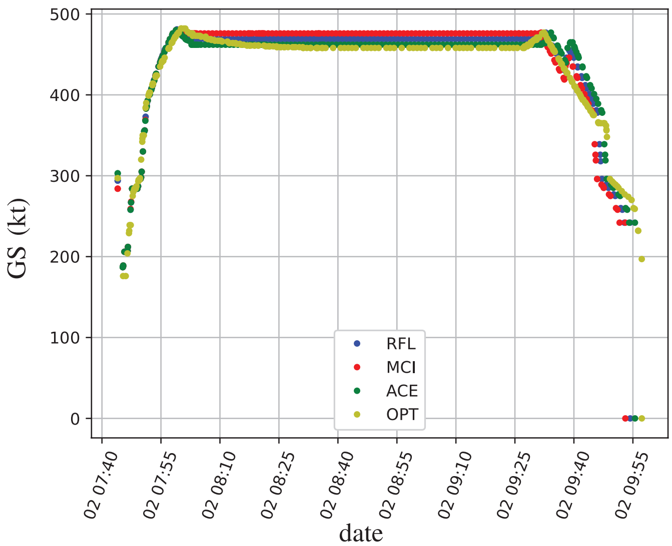


Figure 5. Ground speed (GS) vs. time for a representative aircraft

IV. RESULTS

In Table I the results include not only contrail and fuel consumption costs but also CO_2 and NO_x, which are the main costs of the typical emissions in aviation. The values are computed making use of Equation 6 in any trajectory and case study.

$$
\begin{aligned}
C_{total} = C_{fuel} \cdot (m_{final} - m_{initial}) + \\
+ C_{CO_2} \cdot m_{CO_2}(tonnes) + \\
+ C_{NO_x} \cdot m_{NO_x}(tonnes) + \\
+ C_{cont} \cdot t_{cont}
\end{aligned} \tag{6}
$$

The persistent contrail formation regions exist at lower FLs that are also colder and for the higher FLs exist in the hotter regions nearer to the Equator. Thus, planning for minimum climatic impact is also affected by the actual spatial region where the flight takes place. Also, there is a big difference between the RFL and the minimum climatic impact trajectories. The decrease in emission is of a 41.5%, with only an increase of 4% in the fuel consumption. In comparison with the aircraft ceiling (minimum fuel consumption trajectory that would be actually possible), the minimum climatic impact keeps providing better values for emission generation, still with a slight increase in fuel.

NO_x and contrail emissions are non-negligible under any circumstance. Around 30% and 50% respectively, are the share of these emissions with respect to the total generation. Specially in long-term share, the NO_x takes around 50% of the total share (contrails associated emission have more impact in the short-term regime)

The fuel consumption associated to the optimum trajectories is small when compared with the rest. This is due to the limitations imposed to the procedural trajectories, especially the instantaneous position altitude that make aircraft fly higher, reducing the fuel consumption. Regarding the emissions, the difference between optimum trajectories and the rest is the definition of the input of the AEM Kernel. The software requires to input the phase flight of each point, thus making the optimum trajectories to the input only as climb and descend.

In terms of total costs, it is the *minimum climate impact case* that obtained the best result, followed by *optimal trajectories*. This result is not only positive for the environment but also for the airlines which always seek for reduction of costs.

Case Study	**Fuel**	CO_2	NO_x	**Contrail**	**Total**
Reference FL	7599.54	740.58	1050.51	1737.71	11128.34
Aircraft Ceiling	7332.24	692.66	982.92	1192.83	10204.65
Min. Climate Impact	7809.77	823.39	1187.78	53.25	9874.19
Optimal Trajectory	7216.62	399.37	467.29	1836.50	9919.78

TABLE I
TOTAL COST ($) SUMMARY PER FLIGHT (TIME HORIZON 20 YEARS)

In Table II the results prove the benefits of flying in Optimal Trajectory configuration compared to the other cases. Indeed, its is consumed a 5% less than the actual Reference FL Case. The reason for this phenomena is that the aircraft is controlled to continuously climb at the cruise phase, maximizing its position altitude at every instant of time and, therefore, minimizing the fuel consumption. Instead, Aircraft Ceiling Trajectory sets a constant cruise FL corresponding to the aircraft service ceiling at the start of cruise phase. Hence, Aircraft Ceiling trajectory portrays a significant improvement in terms of fuel consumption compared to Reference FL Case, but still worse than the Optimal Trajectory. According to the Minimum Climate Impact Case, it was expected to achieve the highest value for the fuel consumption, since depending on the atmospheric conditions, aircraft are forced to choose a lower cruise FL so as to avoid contrail formation.

The total number of conflict recorded during the simulation of TAAM for each case study are represented in Table III it

Case Study	Total FC (kg)	%	Per Flight (kg)
Reference FL	10921771	–	5843.64
Aircraft Ceiling	10537567	96	5638.1
Min. Climate Impact	11223897	103	6005.3
Optimal Trajectory	10371480	95	5549.2

TABLE II
FUEL CONSUMPTION (FC) PROVIDED BY TAAM

is represented. Conflicts have been identified corresponding to the definition provided by TAAM as a "Potential Conflict", see [24].The Reference FL Trajectory registered the lowest number of conflicts, since the trajectories have been generated with ATFM regulations. Both Minimum Climate Impact and Optimal Trajectories counted a superior number of conflicts compared to the Reference FL. It is coherent to obtain this result since there have not been applied any ATFM regulation on them. The Aircraft Ceiling trajectory achieved the worst performance in terms of number of conflicts due to the fact that aircraft are encouraged to select similar cruise FLs. In Figure 6 a simulation busy time was selected to show an example of the conflicts distribution per ATC sectors. RFL is, as it was previously mentioned in the global data, the one with lower number of conflicts. Also, Aircraft Ceiling scenario presents more green areas than the others. If a local conflict behaviour is analyzed, conclusions are very similar. LECM2-TLL1 was selected because it seemed to be a representative one to show the tendency in terms of ATM performances. Its location and size can be seen in Figure 7. Minimum Climate Impact has the greatest values in conflicts with a maximum of 7 conflicts. The others scenarios only the Optimal trajectory and Reference FL scenarios showed more than 2 conflicts.

Case Study	Total Conflicts	%
Reference FL	1737	–
Aircraft Ceiling	3603	207
Min. Climate Impact	2958	170
Optimal Trajectory	2860	166

TABLE III
TOTAL CONFLICTS PROVIDED BY TAAM

Number of movements is an indicator to show airspace capacity. Nominal ATC sector capacity could be set to about 60 aircraft movements. Number of movements among sectors do not present any pattern neither on time or scenario. That means a normal behaviour was observed. In Figure 8 a capture of a busy instant is shown. Note that the more crowded can be found in all scenarios. In conclusion, all sectors show reasonable number of movements. Moreover, if a single sector is studied (LECM2-TLL1) we can observe that maximum values are not simultaneous in time among scenarios, but very similar in shape, see Figure 7.

In the Table IV, there can be observed the mean duration flight time calculated for all the traffic flow of each case study. All the cases studies have a similar flight time, except from the *optimal case*. Indeed, *Optimal Profile Case* that has a mean delay of more than 1 hour compared to the other cases. On the other hand, *minimum climate impact* trajectories manage to reach the destination within the same minute as the RFL trajectories. This is, indeed, a positive result for the these sort of trajectories.

Case Study	RFL	MCI	ACE	OPT
Per Flight[s]	8407,24	8438,78	8447,15	12316,87

TABLE IV
MEAN FLIGHT DURATION TIME FOR EACH CASE STUDY

V. CONCLUSIONS

In conclusion, Minimum Climate Impact trajectories show to be the best option in term of cost ($) due to emissions($CO_2$, NO_x and Contrails) are economically penalized. However, it has been shown that Minimum Climate Impact trajectories present a big number of conflicts in comparison with the Reference FL scenario. This could imply in an increase in ATC workload, so then more effort has to be done to reduce the level of possible conflict from the strategic/pre-tactical phase. Besides, in a low traffic scenario, the one studied in the present paper, number of movements (capacity) seems to be suitable. In terms of flight durations, Minimum Climate Impact trajectories do not seem to sacrifice fight duration to save in contrail cost. Therefore, we have demonstrated with this study that Minimum Climate Impact trajectories could be considered as a good option in a non-busy days and/or when weather conditions could give high probabilities of persistent contrail formation.

REFERENCES

[1] D. L. McCollum, G. Gould, and D. L. Greene, "Greenhouse gas emissions from aviation and marine transportation: Mitigation potential and policies," *Institute of Transportation Studies*, 2010.

[2] 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.

[3] B. Hoskins, "The environmental effects of civil aircraft in flight," *Royal Commission*, 2002.

[4] SESAR Consortium, "The ATM target concept, SESAR definition phase milestone deliverable 3," SESAR Consortium, Tech. Rep., September 2007. http://www.eurocontrol.int/sesar/public [Retrieved 01/09/2009].

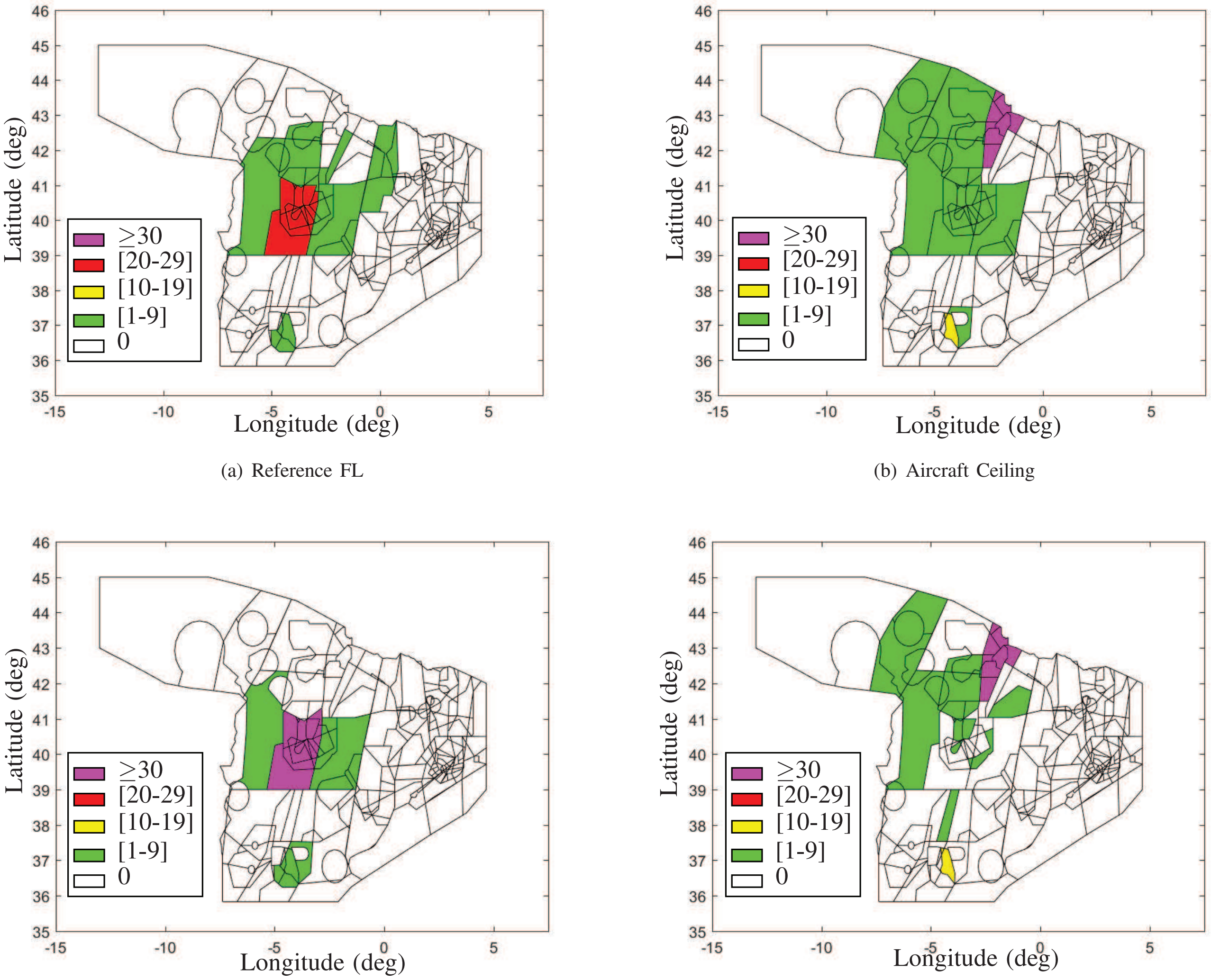
[5] B. S. Hok K. Ng and S. Grabbe, "Optimizing aircraft trajectories with multiple cruise altitudes in the presence of winds," *Journal of Aerospace Information Systems*, vol. 11, no. 1, pp. 35–47, 20144.

[6] 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.

[7] R. Dalmau and X. Prats, "Fuel and time savings by flying continuous cruise climbs: Estimating the benefit pools for maximum range operations," *Transportation Research Part D: Transport and Environment*, vol. 35, no. 62-71, 2015.

[8] B. Sridhar, H. Ng, and N. Chen, "Aircraft trajectory optimization and contrails avoidance in the presence of winds," *Journal of Guidance, Control, and Dynamics*, vol. 34, no. 5, pp. 1577–1584, 2017/09/22 2011. [Online]. Available: https://doi.org/10.2514/1.53378

[9] Y. Lim, A. Gardi, M. Marino, and R. Sabatini, "Modelling and evaluation of persistent contrail formation regions for offline and online strategic flight trajectory planning," in *Sustainable Aviation*. Springer, 2016, pp. 243–277.



(a) Reference FL

(b) Aircraft Ceiling

(c) Min. Climate Impact

(d) Optimal Trajectory

Figure 6. Number of Conflicts over Spain sectors provided by TAAM in a busy time

[10] M. Soler, B. Zou, and M. Hansen, "Flight trajectory design in the presence of contrails: Application of a multiphase mixed-integer optimal control approach," *Transportation Research Part C: Emerging Technologies*, vol. 48, no. Supplement C, pp. 172 – 194, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0968090X14002253

[11] G. O. Imaz and M. Soler, "Atm performance analysis in madrid acc sectors considering optimal aircraft trajectories, icrat'16," 2016.

[12] F. Jelinek, S. Calrlier, I. Crook, K. Martin, J. Smith, and M. N. Vo, "Atm contrail mitigation options environmental study," *EEC/SEE/2005/015. EUROCONTROL Experimental Centre, Bretigny, France*, 2005.

[13] "Total airspace and airport modeler," http://ramsplus.com.

[14] A. Nuic, *User Manual for the Base of Aircraft Data (BADA) Revision 3.6*, Eurocontrol Experimental Center, Bretigny, France, 2005. http://www.eurocontrol.int/eec/public [Retrieved 01/09/2009].

[15] H. Appleman, "The formation of exhaust condensation trails by jet aircraft," *Bulletin of American Meteorological Society*, vol. 34, no. 1, pp. 14–20, 1953.

[16] "Noaa global forecast system (gfs)," https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs.

[17] "Advanced emission model (aem) kernel," https://www.eurocontrol.int/services/aem-advanced-emission-model.

[18] [Online]. Available: www.ampl.com/

[19] "Total airspace and airport modeler," http://ww1.jeppesen.com/industry-solutions/aviation/government/total-airspace-airport-modeler.jsp.

[20] "Jet fuel prices monitor," http://www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx.

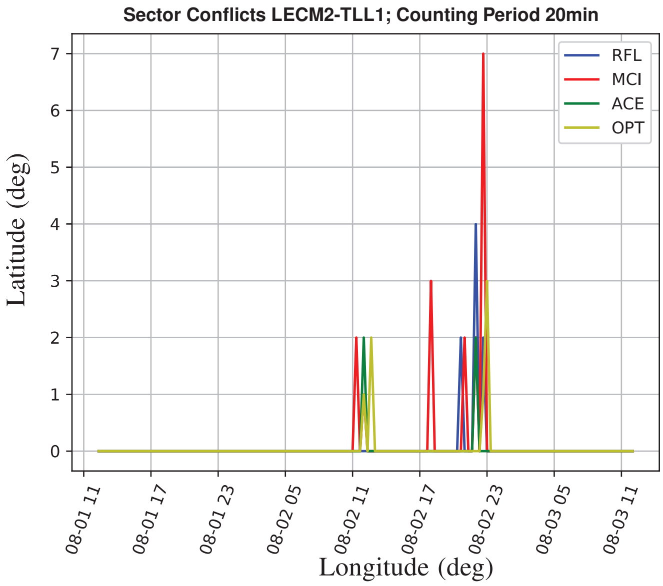
[21] "Us environmental protection agency," https://www.epa.gov.

[22] "Direct global warming potentials: Physical science basis," $https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html$.

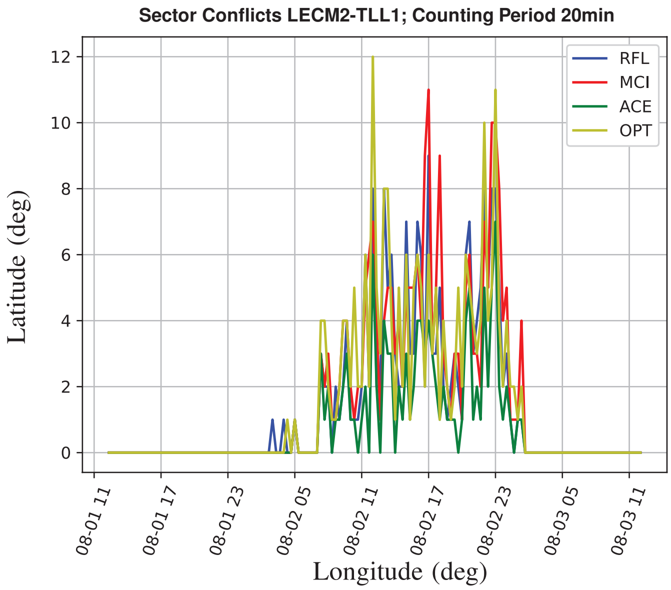
[23] P. Bonami, A. Olivares, M. Soler, and E. Staffetti, "Multiphase mixed-integer optimal control approach to aircraft trajectory optimization," *Journal of Guidance, Control, and Dynamics*, vol. 36, no. 5, pp. 1267–1277, 2013.

[24] a. B. c. Jeppesen, "Total airspace and airport modeller (taam) product profile," *Links*, 2015.

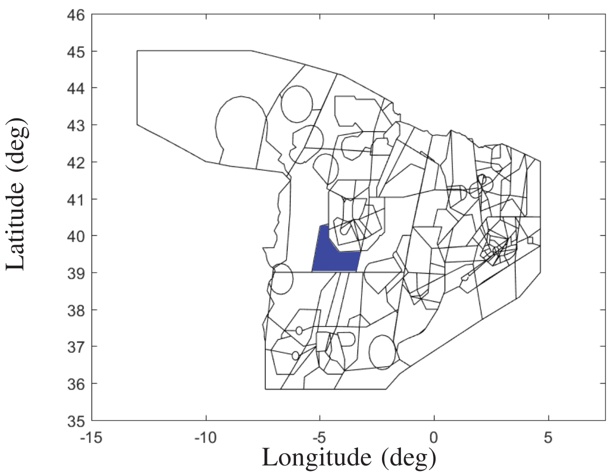
VI. Copyright Statement



(a) Number of conflicts in LECM2-TLL1



(b) Number of movements in LECM2-TLL1



(c) ATC sectors in Spain, the posted example LECM2-TLL1 is shown in violet colour.

Figure 7. Individual sector study

their paper as part of the EIWAC2017 proceedings or as individual off-prints from the proceedings.

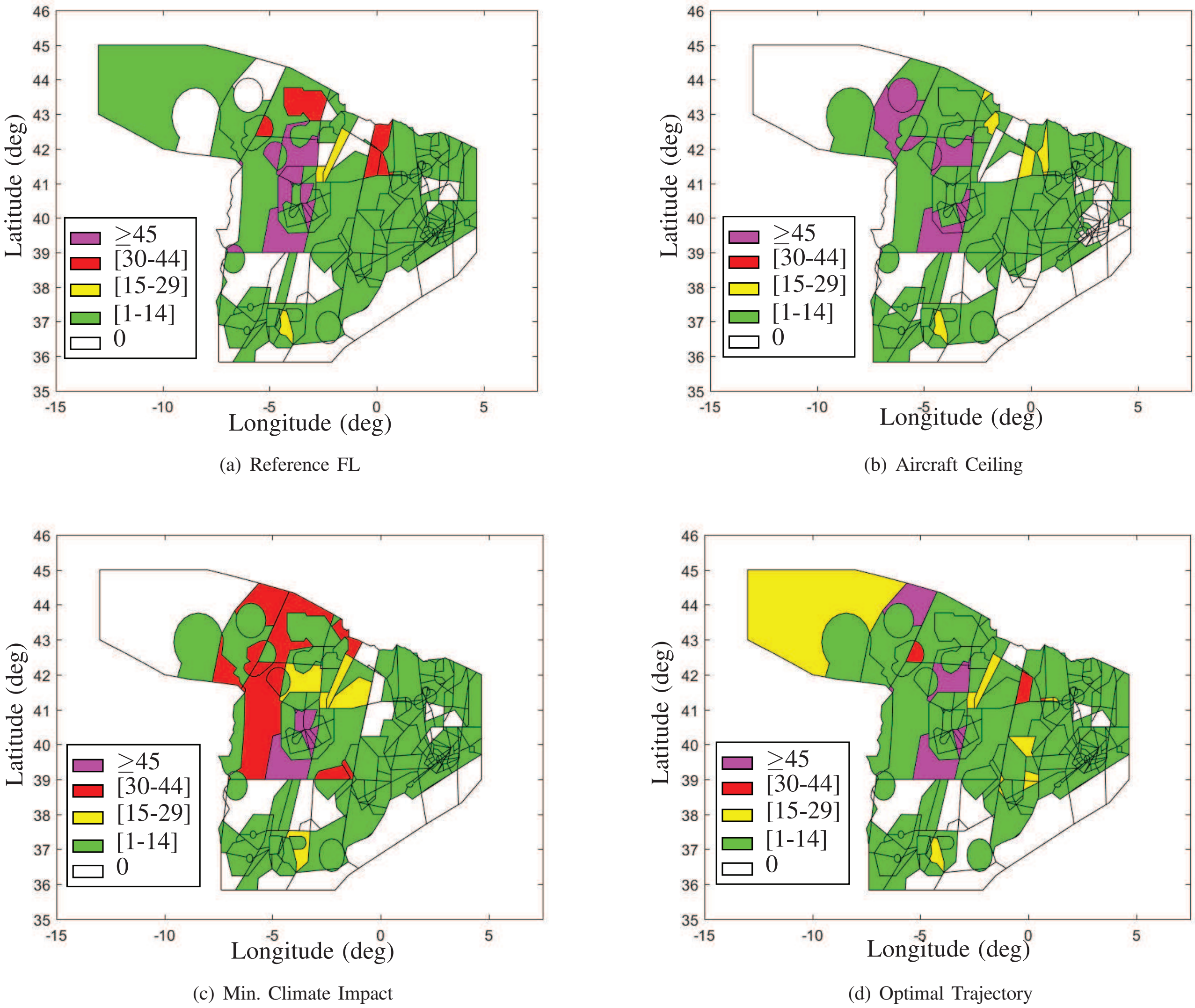


Figure 8. Number of movements over Spain sectors provided by TAAM in a busy time