Novel engine concept to suppress contrail and cirrus cloud formation

F. Noppel*, R. Singh
Cranfield University, Bedfordshire, UK

M. Taylor
Rolls-Royce, Derby, UK

Keywords: sustainable aviation, novel engine concept, contrail avoidance

ABSTRACT: Greenhouse gas emissions, contrails and artificially induced cirrus clouds are the principal pollutants from air traffic which contribute to the anthropogenic global warming. Recent climate assessments have stressed the importance of contrails and aviation induced cirrus clouds. They might contribute more than all other aircraft emissions combined. Revolutionary technologies will contribute to accommodate the increasing demand in air transport at a sustainable level. In this paper, a novel propulsion concept is presented with the intention to provide greener propulsion for future aircraft. It is based on gas turbine technology, derived from the intercooled and recuperated engine concept. Exhaust water condensation is facilitated inside the engine to avoid the formation of contrails in the plume. Particles and aerosols are being scavenged from the exhaust gases during condensation. The condensed water is redirected into the combustor to mitigate NO_x emissions via water injection technique. The new concept allows higher thermal efficiencies than conventional designs to cut back greenhouse gas emissions. It is concluded that significant advances in heat exchanger technology are required to make this concept feasible.

1 INTRODUCTION

There is evidence that anthropogenic greenhouse gas emissions have an impact on the Earth's radiation budget and cause a long term increase in the Earth's mean surface temperature. Air traffic pollutants are placed in the upper atmosphere where their impact is different. Water vapour and aerosol emissions are responsible for the formation of persistent contrails and cirrus clouds, both causing a net heating of the Earth's atmosphere. The steady state response in the Earth's mean surface temperature due to a certain pollutant can be related linearly to its radiative forcing (RF). There is the potential that the RF from persistent contrails, contrail cirrus, secondary cirrus and cirrus cloud modification exceeds the RF of all other emissions from air traffic combined (Sausen et al., 2005).

Early jet engines suffered from poor component efficiencies, restricted turbine inlet temperatures and low achievable pressure ratios. This had a deteriorating effect on the fuel economy of early models. The advent of advanced combustor technology, high component efficiencies, new materials, blade cooling techniques, higher pressure ratios thanks to multi spool arrangements, and large bypass ratios caused significant advances in engine performance. There is still potential for further improvements in fuel economy considering conventional engine architecture. However, these improvements take place on a system level and are becoming increasingly difficult to achieve. The theoretical limit for thermal efficiency is 60%, whereby a stoichiometric turbine entry temperature (TET) and an overall pressure ratio (OPR) in excess of 80 are considered (Green, 2005). The theoretical limit for propulsive efficiency is 92.5% which represents an open rotor configuration. This approach stays in conflict with NO_x emission standards and will cause an increase in contrail cover due to the increase in overall efficiency. However, revolutionary changes in engine design can lead to further significant advances in engine fuel economy and environmental compatibility.

* *Corresponding author:* Frank Noppel, Cranfield University, Bedfordshire, MK43 0AL, UK. Email: f.g.noppel@cranfield.ac.uk

2 RATIONALE

The following requirements are set for a novel engine concept: significantly increased thermal efficiency, a reduction in water vapour, soot and aerosol emissions to avoid the formation of contrails and cirrus clouds, and low NO_x emissions. The engine weight should not offset engine performance improvements. Although theoretical approaches which utilise fuel cells and similar mechanisms may be feasible (Alexander et al., 2002), they require significant deviation from current gas turbine practice. Hence, it would be more desirable to provide a practical solution with respect to existing gas turbine technology which operates with any available hydrocarbon based fuel.

The novel concept presented herein is based on the intercooled and recuperated engine cycle in a two spool arrangement as shown in figure 1(b). A substantial improvement in thermodynamic work potential can be realized by combining intercooling and exhaust regeneration. The intercooler is a heat exchanger placed between the low pressure compressor (LPC) and high pressure compressor (HPC). The flow on the cold side of the intercooler is usually bypass air. Intercooling reduces the work required for the compression of the air in the HPC. The hot gases leaving the low pressure turbine (LPT) are used to heat the pre-combustor air in the recuperator, so more heat is used to generate useful work.

Contrails form in the exhaust plume of an aircraft if saturation with respect to water occurs during the mixing process of the exhaust gases with ambient air. Considering current engine architecture, they form more likely with increasing overall engine efficiency (Schumann, 2000). Hence, fuel burn and contrail formation are in conflict with each other. The formation of contrails would not occur for low exhaust water content at relatively high temperature. Water could be removed from the exhaust if the temperature after the LPT is sufficiently reduced to provoke water condensation within the engine. This can be accomplished with an intercooled and recuperated cycle in a novel arrangement. Therefore, the flow exiting the recuperator is further cooled by applying an additional heat exchanger: the condensation stage. For a sufficiently low temperature, this will cause condensation of the exhaust water within the engine. Condensation occurs also on particles and aerosols contained in the exhaust. This effect can be utilized to provoke particle and aerosol scavenging inside the engine. The water from the condensation stage can be stored on the aircraft or released into the atmosphere in liquid or ice phase for precipitation. A fractional part of the condensed water is redirected into the combustor to suppress the formation of NO_x through water injection. The dry and cold air leaving the condensation stage is used to chill the compressor air in the intercooler. This causes an increase of the flow temperature of the core exhaust. Because contrails are less likely to form with increasing exhaust temperature, it has the effect of further reducing the potential for contrail formation.

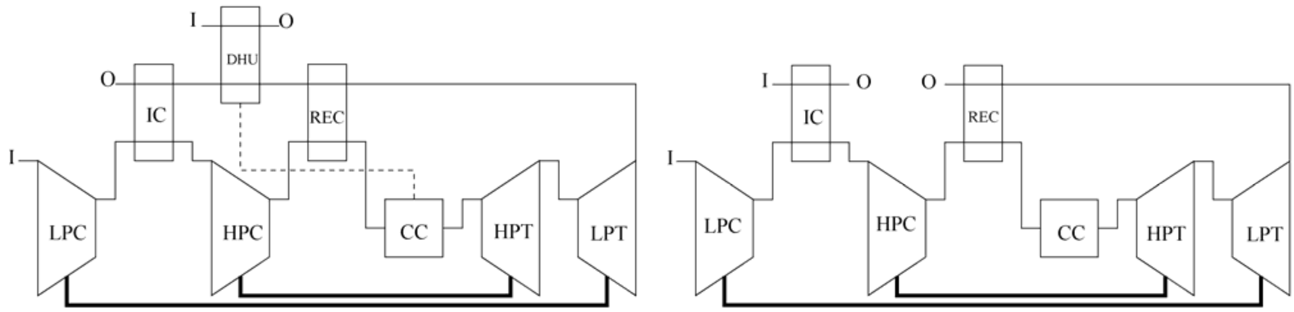

Figure 1: novel concept (a) vs. intercooled recuperated engine cycle (b)

Figure 1(a) shows the flow schematic of the novel engine concept. Compared to the ordinary intercooled and recuperated cycle, the major differences are that the conventional intercooled recuperated cycle works with bypass air on the cool side of the intercooler whereas in the novel concept bypass air is used in the condensation stage and the intercooler operates with core air on both sides.

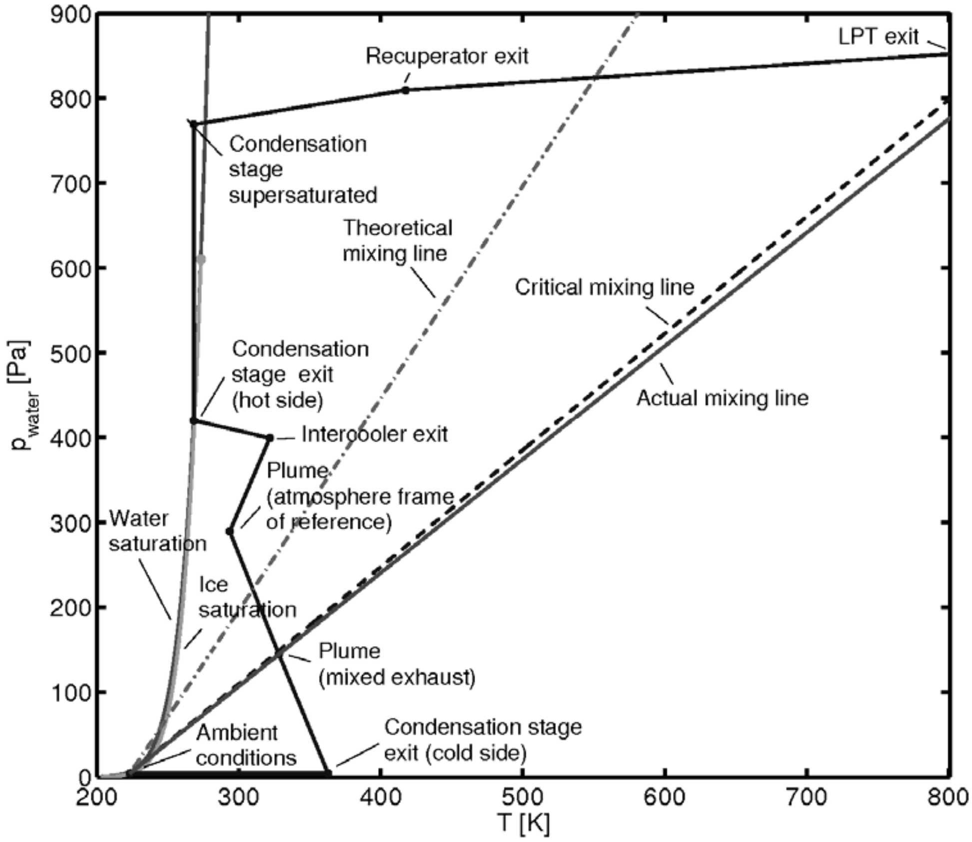

Figure 2: engine stations on a phase diagram of water

Figure 2 shows the water partial pressure on a phase diagram of water for different stations within the engine and in the plume. The water partial pressure in the flow exiting the hot side of the condensation stage is determined by the water saturation pressure at the flow temperature. In this study, the water saturation pressure is calculated from Flatau et al., 1992. Whereas static flow temperatures and pressures are considered for the stations within the engine, stagnation properties relative to the atmosphere frame of reference are considered in the plume. Mixing is assumed to take place adiabatically and isobarically. The two exhausts, the core exhaust and the exhaust from the cold side of the condensation stage, are assumed to mix prior to the mixing with ambient air. The actual mixing line represents the mixing of the mixed exhausts with ambient air. Furthermore, figure 2 shows also the critical mixing line, which is a tangent to the water saturation pressure line originating from the ambient state of the atmosphere. Together with the actual mixing line, it is used for contrail prediction. If the actual mixing line is below the critical mixing line, contrail formation is not facilitated. This is because contrails only form if the actual mixing line surpasses the region for which water is present in the liquid phase in a phase diagram (Jensen, 1998). Additionally, the theoretical mixing line is shown. It represents the mixing line of the mixed exhaust with ambient air if no dehumidification took place. Originating from the ambient state of the atmosphere, its slope is calculated from (Schumann, 2000)

$$G_{theo.} = \frac{c_p EI_{H_2O} p_a}{(1-\eta_0) q_{net} \varpi} \qquad (1)$$

where c_p is the specific heat capacity of air, EI_{H2O} is the water emission index for a certain fuel, p_a is the ambient static pressure, η_0 is the overall engine efficiency, q_{net} is the fuel net calorific value and ω is the molar mass ratio of water to air. The actual mixing line and the theoretical mixing line are identical if water condensation is not facilitated within the engine.

3 CYCLE STUDY

A cycle study has been carried out for performance prediction and to comprehend the system behaviour. To this end, a performance model, a standard atmosphere model and a contrail prediction model were linked together. The performance model considers a thermodynamic cycle as shown in figure 1(a) delivering shaft power to drive a fan or a propeller. The propulsive efficiency is not taken into account in the calculations. The cycle is solved so that the exhaust exiting the cold side of the intercooler matches ambient velocity and does not produce a propulsive force. The cooling air exiting the cold side of the dehumidifier produces a propulsive force due to its increase in momentum. Even though it is small, it is taken into account when calculating the overall thermal efficiency. The design variables are engine overall pressure ratio, turbine inlet temperature and the ratio LPC pressure ratio to HPC pressure ratio (R). Isentropic compressor efficiencies are assumed to be 0.88, turbine efficiencies are assumed to be 0.92, nozzle and inlet efficiencies are assumed to be 0.99. The combustor total pressure loss is assumed to be 4%, heat exchanger total pressure losses are assumed to be 5% for each side. These component efficiencies and pressure losses represent advanced technology levels. The water content of the flow exiting the condensation stage is determined by its static temperature and pressure. Therefore, the flow Mach number through the heat exchanger was assumed to be 0.1 for all calculations. All calculations are carried out assuming constant fluid properties. Ambient conditions are determined by the cruise altitude using the ISA standard atmosphere model and specifying ambient relative humidity with respect to ice.

A commercially available optimisation algorithm was used for cycle optimisation. The ratio of the actual mixing line slope to the critical mixing line slope ($G/G_{crit.}$) acts as an indicator of whether contrail formation is facilitated or not. Values above 1 imply contrail formation whereas values below 1 imply no contrail formation. The ratio of the actual mixing line slope to the theoretical mixing line slope ($G/G_{theo.}$) is used to predict whether condensation takes place inside the engine. The ratio can only have values of 1 or below. Values below 1 imply that water is removed from the exhaust; a value of 1 implies the opposite. Furthermore, the temperature differences between the inlet and outlet for each side of the heat exchangers are calculated. The cumulative of the maximum temperature differences (ΔT_{HE}) is used as an indicator of the overall size of all heat exchanging devices.

With a fixed value of TET and OPR, the cycles were optimised for maximum thermal efficiency ($\eta_{thermal}$) varying R. The considered values for TET are 1700K to 2000K and for OPR are 19 to 49. Flight conditions are 10000m altitude at Mach 0.8 with an ISA temperature deviation of 0K. Three levels of ambient ice supersaturation are taken into account: 100%, 130% and 150%. The effectiveness of all heat exchangers is assumed to be 90%.

Although condensation of water within the engine is facilitated for all cycles considered, the water content is not low enough to avoid the formation of contrails[1]. Both exhaust water content and thermal efficiency are dependent on R. Therefore, the objective function was modified to give $G/G_{crit.}$ for $G/G_{crit.}>1$ and $-\eta_{thermal}$ for $G/G_{crit.} \leq 1$. This resulted in the optimisation algorithm minimising $G/G_{crit.}$ to obtain a cycle facilitating contrail avoidance and optimising for maximum thermal efficiency. Cycles optimised for contrail avoidance are not operating at maximum achievable thermal efficiency anymore and the value for ΔT_{HE} increases. Figure 4 shows the change in ηthermal and ΔT_{HE} for RH_i=100% and RH_i=150% compared to cycles optimised for maximum thermal efficiency only. For the spaces left out, the performance calculation did not converge and no solution exists. The thermal efficiency for the cycles optimised for maximum thermal efficiency only is in the range between 0.56 and 0.65. Efficiency penalties are more severe if higher ice supersaturation is considered during optimisation and for larger OPR's. The same is true for ΔT_{HE}.

Considering a cycle with TET=2000K, OPR=31 and ISS = 150%, the thermal efficiency of the cycle optimised for contrail avoidance is about 0.64. Assuming a propulsive efficiency of 93%, the overall engine efficiency becomes 0.6. This is still well above the maximum theoretical achievable efficiency of engines with conventional architecture.

[1] It would be facilitated for sufficiently low OPR's and TET's

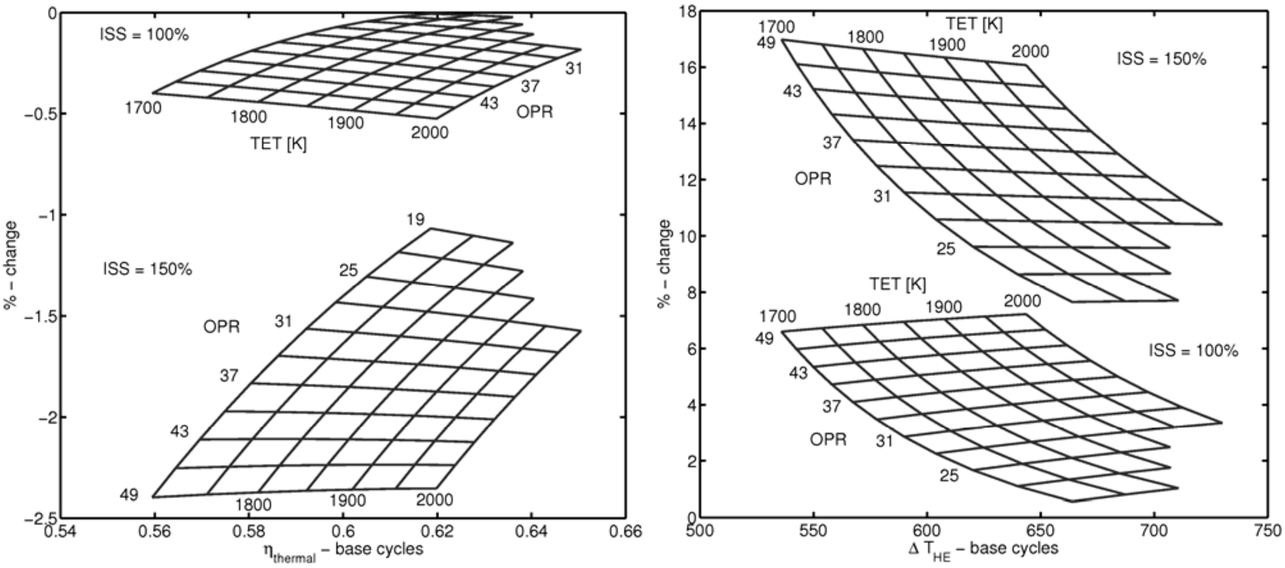

Figure 4: changes in $\eta_{thermal}$ and ΔT_{HE} compared to cycles optimised for $\eta_{thermal}$ only

Further results are shown in figure 5 on a specific fuel consumption (SFC) - specific work (W_s) chart and ΔT_{HE} - $G/G_{theo.}$ chart. An ambient ice supersaturation of 150% is considered. It is desirable to choose a cycle with low specific fuel consumption and high specific work output to reduce the size of the turbomachinery. This can be achieved with high TET's and low OPR's. However, high values of TET and low values of OPR imply relatively large values of ΔT_{HE} which is not desired. Water condensation occurs inside the engine for all considered cycles because the ratio $G/G_{theo.} \leq 1$ in all cases.

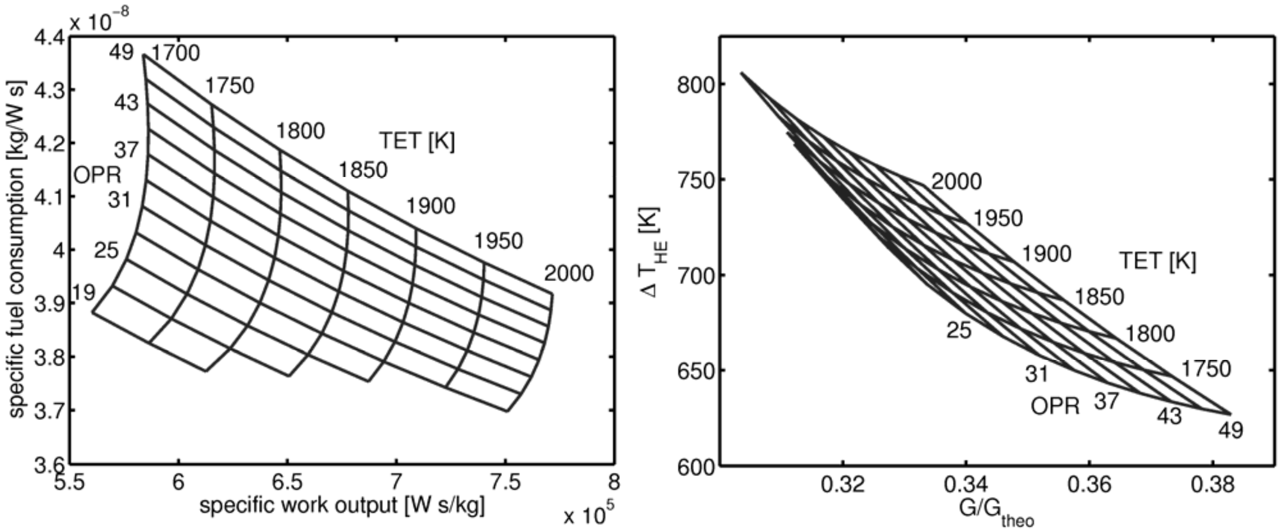

Figure 5: cycle study results of the new engine concept optimised for maximum $\eta_{thermal}$ and contrail avoidance considering 150% ambient ice supersaturation

4 NO_X REDUCTION

A reduction in primary zone temperature can be achieved through water injection into the combustion chamber. A water flow rate 2 times the fuel flow rate can reduce NO_x emissions by up to 80% (Lefebvre, 1983). The feasibility of water injection has been demonstrated by Daggett, 2004. Liquid water from the condensation stage would provide water for injection into the combustion chamber. The water content in the flow between the combustor and condensation stage will increase until part of the water is drawn off from the condensation stage. Drawn off water can either be stored on board the aircraft or released into the atmosphere for precipitation. The novel engine concept allows any desired water flow rate into the combustor.

5 FURTHER CONSIDERATIONS

Heat exchanger size is predominantly dependent on heat exchanger effectiveness and the desired temperature change. The cycles respond with an increase in ΔT_{HE} to a decrease in heat exchanger effectiveness'. A relatively high effectiveness in the condensation stage is crucial in order to achieve a low temperature within the engine that facilitates water condensation. This temperature is within the ambient temperature range, so the temperature difference between the flows that exit the condensation stage at the core side and enter at the bypass side is relatively small. Hence, it can be concluded that advanced heat exchanger technology in terms of heat transfer, weight, and pressure loss is essential for the feasibility of this concept. Super conducting heat transfer material is being investigated and similar materials could be available in the future (Qu, 2000).

Because the required temperature in the condensation stage is determined by the temperature at which water condensation occurs, a reduction in water saturation pressure would cause a reduction in the required temperature difference. A reduction in water saturation pressure could be achieved applying curved surfaces within the heat exchanger (Kelvin effect). Fluid properties could be changed applying exhaust seeding in order to activate condensation surfaces and reduce the partial pressure at which condensation occurs.

6 SUMMARY AND FINAL REMARKS

A novel propulsion concept is proposed which exhibits significantly reduced emissions, in particular CO_2, NO_x and water vapour, soot and aerosols to avoid the formation of contrails and aviation induced cirrus clouds. It is intended to encourage the aeronautical community to further discuss this concept or develop other concepts with similar purposes.

This novel concept can operate at higher thermal efficiency than current designs and the formation of contrails is avoided. This is achieved by combining the advantages of heat exchangers in terms of performance improvement and to enforce water condensation inside the engine. A reduction in NO_x emissions is achieved through water injection. Any water to fuel ratios are theoretically achievable and water injection could take place during the entire journey.

We conclude that the feasibility of the cycle depends on the available future heat exchanger technology. The results of this study are based on a cycle study where mechanical issues are not addressed. It is intended to further investigate this propulsion concept using a comprehensive aircraft and engine model.

7 ACKNOWLEDGEMENTS

This study is part of a Ph.D. project sponsored by the Cranfield Rolls-Royce University Technology Centre in Gas Turbine Performance Engineering.

REFERENCES

Alexander, D. Y.-M. Lee, M. Guynn, and D. Bushnell, 2002: *Emissionless aircraft study,* AIAA-2002-4056

Daggett, D., L. Fucke, R. C. Hendricks, and D. J. Eames, 2004: *Water injection on commercial aircraft to reduce airport NOx*, AIAA-2004-4198

Flatau, P. J. , L. Walko, and W. R. Cotton, 1992: Polynomial fits to saturation pressure, *Journal of Applied Meteorology*, 31, 1507–1513

Green, J. E., 2005: Mitigating the environmental impact of aviation: Opportunities and priorities, *The Aeronautical Journal*, 109, 361-416

Jensen, E. J. , O. B. Toon, S. K. Kinne, G. W. Sachse, B. E. Anderson, K. R. Chan, C. H. Twohy, B. Gandrud, A. Heymsfield, and C. Miake-Lye, 1998: Environmental conditions required for contrail formation and persistence, *Journal of geophysical research*, 103, 3929-3936

Lefebvre, A. H., 1983: *Gas turbine combustion*, Hemisphere Publishing, USA, 0-07-037029-X, pp 485

Qu, Y., 2000: *Superconducting heat transfer medium*, U.S.P. 6,132,823

Sausen, R., I. Isaksen, V. Grewe, D. Hauglustaine, D. Lee, M. Gunnar, M. O. Kohler, G. Pitari, U. Schumann, F. Stordal, and C. Zerefos, 2005: Aviation radiative forcing in 2000: An update on IPCC (1999), *Meteorologische Zeitschrift*, 14, 555–561

Schumann, U., 2000: Influence of propulsion efficiency on contrail formation, *Aerosp. Sci. Technol.*, 4, 391–401

On how to consider the Earth's Atmosphere in Aircraft Design

R. Egelhofer*
Technische Universität München – Lehrstuhl für Luftfahrttechnik, Garching, Germany

C. Marizy
Airbus France, Toulouse, France

C. Bickerstaff
Airbus UK, Filton, Bristol, UK

Keywords: Aircraft design, two-stage operations, atmospheric impact

ABSTRACT: The increasing knowledge in atmospheric sciences and modelling has started to enable the environmental assessment of aircraft emissions. Aeronautical engineering must therefore begin to consider the atmosphere in future aircraft design. Aviation being a complex business with many different stakeholders, both configurational and operational design solutions for minimum atmospheric impact have to be evaluated for real flight operations. This paper presents a methodology providing a systemic structure for such evaluations. Two-stage operations illustrate this methodology as an example that incorporates both configurational and operational aspects. The methodology highlights the fact that, in a global operational context, there remains a large gap between theoretical benefits and actual performance.

1 INTRODUCTION

Civil aviation is confronted with increasing public attention concerning its impact on the environment. Whereas noise has been the principal cause of anxiety since the early years of commercial air transport, air quality around airports and climate change have only been considered more recently. The aviation business is very complex, since many different stakeholders – authorities, air traffic control (ATC), airlines, airports, aircraft and engine manufacturers – have to satisfy their respective needs and contribute to a safe and economic means of transport for leisure and business passengers.

When it comes to reducing the aviation's environmental impact, each of the contributors is asked to evaluate his part of the story and to undertake any reasonable effort of mitigation. Aircraft and engine manufacturers have achieved large increases in fuel efficiency over the last decades, which, apart from the economic interest, have reduced the environmental impact. Today, it appears that other stakeholders still have large potentials to further mitigate the impact of aviation on the environment. According to Lufthansa German Airlines, ATC improvements could allow for a reduction of 8 % to 18 % of fuel consumption over Europe and, military airspaces still cause substantial deviations leading to a higher fuel burn (Lufthansa, 2006). Yet, reducing the impact on climate change still remains a task of the aircraft designer.

The contribution of aviation to climate change was estimated at around 3.5 % of the global anthropogenic radiative forcing for the year 1992 in the IPCC Special Report (Penner et al., 1999). This impact is determined by the quantity, type and location of engine exhaust gas emissions. These parameters are mainly, though not exclusively, determined through the design of an aircraft and its engine. Whereas non-optimal flight routing, holding patterns and other extra-fuel-consuming events are difficult to account for in aircraft design, as they are difficult to predict, the scheduled flight network is well defined and can therefore be interlinked with the design process for new aircraft (i.e., along with other parameters such as need for specific ranges and/or capacities). This linkage is particularly important when it comes to evaluating the atmospheric impact of an aircraft concept.

* *Corresponding author:* Regina Egelhofer, Technische Universität München, Lehrstuhl für Luftfahrttechnik, Boltzmannstr. 15, D-85747 Garching, Germany. Email: egelhofer@tum.de

The methodology presented here provides a systemic superstructure for the evaluation of the atmospheric impact of an aircraft concept, embedded in global operations, and thus prepares for its optimisation for minimum contribution to climate change. Two-stage operations are assessed in this regard, as concrete example for atmosphere-compatible design approaches. This example will also highlight operational implications of such approaches for "environmental" aviation.

2 RELEVANCY OF THE ENVIRONMENT IN AVIATION

The protection of the environment has influenced the development of the aviation system for a long time. In the public arena, aviation is well appreciated by business and tourists on the one side, strongly analysed and criticised on the other side. Aircraft have become far more fuel-efficient through advances in lightweight structures, the reduction of aerodynamic drag and more efficient jet engines. Emission indices of nitrogen oxides (NO_x) have been and are still being further reduced with innovative combustor concepts and heat exchangers etc. (Egelhofer, in press). As fuel contributes to a significant extent to aircraft operating cost and as fuel prices continue to increase, the reduction of fuel consumption remains a major concern for future aircraft. The impact of an individual aircraft on climate change should thus continue to be reduced in future.

However, it is not the aircraft itself, but its operation that has an environmental impact, so that the aviation system as a whole needs to be considered when evaluating the atmospheric impact of an aircraft concept. Many different stakeholders have an impact on the "production" of each flight.

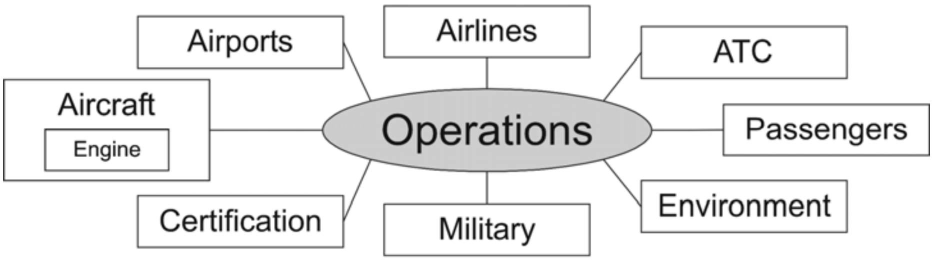

Figure 1. Relevant stakeholders of aviation

The consideration of the atmosphere in aircraft design turns out as a complex task as not only does it involve the aircraft and engine manufacturers, but also airlines (business models, fleet planning), airports (capacity, traffic management, environmental restrictions), Air Traffic Management (ATM) and ATC (quality of flight routing, congestion), certification and even the military (restricted airspaces). Passengers are involved both by their personal requirements for a flight (e.g., desire for convenience and speed and environmental consciousness) and by their behaviour during the flight (e.g., an aircraft has to fly faster to catch up following delays caused by passengers arriving late, and thus consumes more fuel).

Each of the issues referred above is interlinked directly or indirectly with aircraft design. The design engineer then has the difficult task of trying to handle many different and often contradictory requirements, one of which is a minimum contribution to climate change.

3 DESIGN PROCESS FOR MINIMUM ATMOSPHERIC IMPACT

In current aircraft optimisation loops, noise starts being integrated as important requirement, even at preliminary design level. As referred above, emissions are largely minimised in aircraft design through the minimisation of fuel consumption, which also impacts on direct operational cost. An effective evaluation of aviation's emissions' impact on the atmosphere is undertaken only after attempting to consider the complete problem and does not apply to a single aircraft type, but rather to the global fleet.

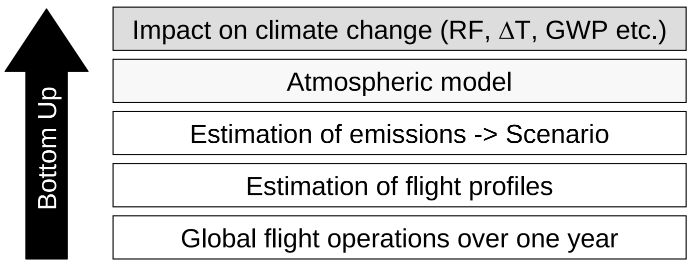

Figure 2. Current evaluation of the atmospheric impact of aviation: bottom up, no feedback.

Our approach embeds a new aircraft concept in a global fleet on a real route network. With a market forecast and aircraft performance data, global emission scenarios are created. This process enables the assessment of the various operational adaptations such as new flight altitudes or speeds, which will result from the new aircraft concept. For the subsequent evaluation of the impact on the atmosphere, some atmospheric metrics and modelling will be included in the process as soon as these are available. A sufficient reliability of the metrics is a prerequisite for their confident integration into the design process. Varying aircraft parameters of the investigated aircraft concept enables a comparative study between the resulting emission scenarios and their respective atmospheric impacts.

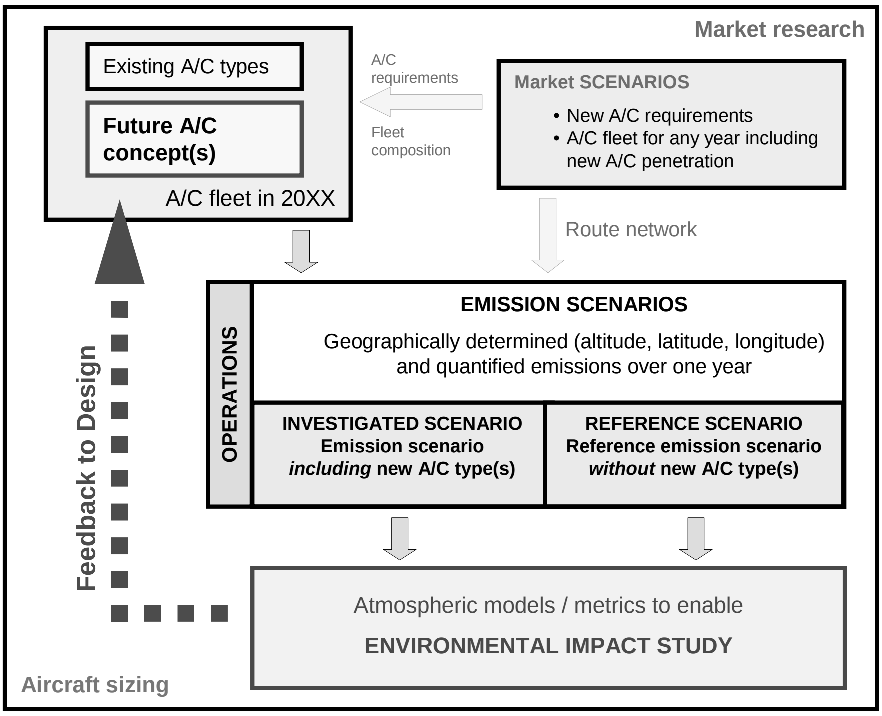

Figure 3. Design approach for minimum atmospheric impact, with feedback

For the application of the methodology for new aircraft, data for the future global fleet have to be estimated, which necessitates sound support from market research. The comprehensive character of the approach makes a proper organisation and setting up of parameters and methods essential. The precision levels of all modules have to be synchronised and the consistency of the data has to be guaranteed. Not only does a real integration of the atmospheric impact in aircraft design enable its evaluation or minimisation, but it also enables tradeoffs with noise and local air quality, that tend to foster other design solutions. The approach aims at contributing to a reasonable compromise of design parameters for economically viable, environmentally friendly and thus sustainable aircraft.

4 TWO-STAGE OPERATIONS (TSO) AS EXAMPLE OF USE OF THE METHODOLOGY

Two-stage operations (TSO) reflect both operational and configurational advances in design and were thus chosen as illustrative example of the methodology. For the time being, fuel burn (proportional to CO_2 and H_2O emissions) was chosen as metric for the atmospheric impact of aviation.
In steady flight, the thrust of an aircraft is equivalent to its drag, most of which is caused by the aerodynamic lift of the aircraft. Consequently, an increased aircraft weight demands more thrust and leads to higher fuel consumption. On longrange flights, aircraft use a lot of fuel just to transport fuel. On the other hand, the takeoff procedure is very fuel-consuming. For each aircraft, a distance for minimum fuel consumption per flown kilometre can be determined. In the example given in Figure 4, the optimum stage length is 4300 km.

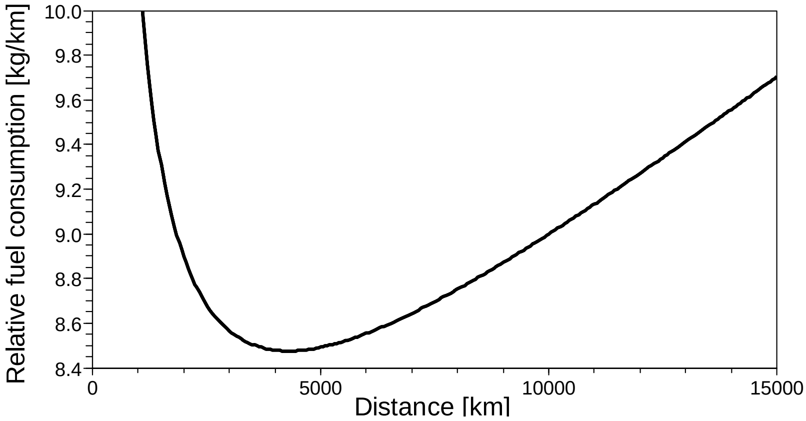

Figure 4. Relative fuel consumption in kg/km for an example longrange aircraft

An approach to reducing the fuel consumption for longrange flights is to separate the flown distance into two or more stages ("two-stage operation" or "multi-stage operation"), of which each length should be as close as possible to this minimum.

4.1 *Theoretical fuel reduction potential with TSO*

If the distance to be flown is only slightly longer than the optimum distance, a TSO may not save fuel. The curve plotted in Figure 4 can be approached by a function of the type

$$y = ax + b + \frac{c}{x} \tag{1}$$

where x is the distance to be flown and y is the relative fuel consumption per flown kilometre. The parameters a, b and c are chosen such that the curve is best estimated, e.g. for stage lengths between 300 km and 12,000 km. The potential relative fuel saving of a TSO is

$$z = y_{total} - \frac{y_1 \cdot x_1 + y_2 \cdot x_2}{x_{total}} \tag{2}$$

where x_1 and x_2 are the lengths of the two stages, y_1 and y_2 are the respective relative fuel consumptions of the two stages and x_{total} is the total distance with a total relative fuel consumption of y_{total}, if flown in one flight. Considering that $x_{total} = x_1 + x_2$ and equation (1), we get

$$z = 2ax_1 - \frac{c + 2ax_1^2}{x_{total}} \tag{3}$$

Dividing (3) by (1) gives the potential fuel economy e in percent:

$$e = \frac{-2ax_1^2 + 2ax_1x_{total} - c}{ax_{total}^2 + bx_{total} + c} \tag{4}$$

Plotting function $e(x_{total},x_1)$ shows for which total distances and which partial distances considerable fuel savings can be obtained, if operating as TSO:

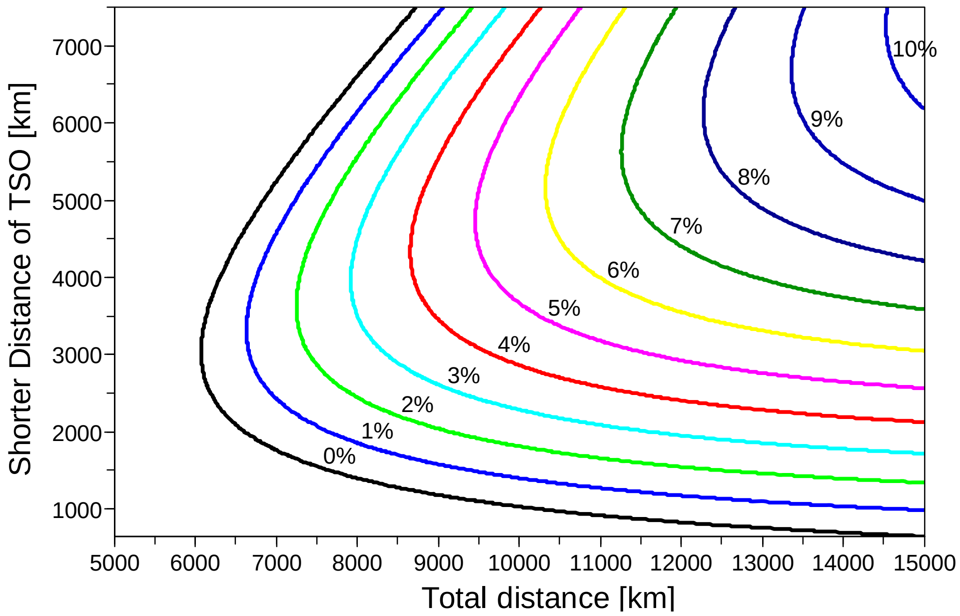

Figure 5. Theoretical fuel economy for an example longrange aircraft with TSO in percent (isolines), depending on the total distance (abscissa) and the shorter of the two stages with TSO (ordinate).

4.2 *Market share of TSO-capable routes*

Considering a fuel saving of 2 % "interesting", routes of more than 7200 km would be worth a TSO with the considered example aircraft. In the global air traffic (OAG data from 2005), such flights represent only 2.7 % of all annual flights by aircraft greater than one hundred seats, but 27 % of available seat-kilometres (see Table 1).

Table 1. Theoretical maximum fuel economy operating in two stages with an existing longrange aircraft and respective fractions of flights and available seat kilometres of the global traffic of aircraft with more than one hundred seats.

Theoretical fuel economy	Distance greater than [km]	Fraction Flights	Fraction ASK
0%	6100	4.2%	37%
1%	6600	3.4%	32%
2%	7200	2.7%	27%
4%	8700	1.5%	17%
6%	10,300	0.43%	5.5%
8%	12,300	0.05%	0.5%

This means that, despite the high fraction of "TSO-capable" routes in the global traffic of aircraft with more than one hundred seats, operating the aircraft considered here on all flights above 6100 km at the respective optimum stage length, would theoretically save only around one percent of the global fuel consumption.

4.3 *Theoretical reduction potential with redesigned aircraft*

A higher potential for savings could be attained, if aircraft were designed for shorter ranges. The smaller fuel quantities needed would allow a lower structural weight of the aircraft. A lighter structure again leads to reduced fuel consumption (see 4.1), which feeds back into a reduced structural weight. According to Green et al. (2005), an aircraft designed for 7400 km operating in stages on current real routes would save 10 % in fuel burn compared to an aircraft designed for 14,800 km. Compared to 4.1, this estimation allows for real routes. The theoretical potential of redesigning aircraft would be higher:

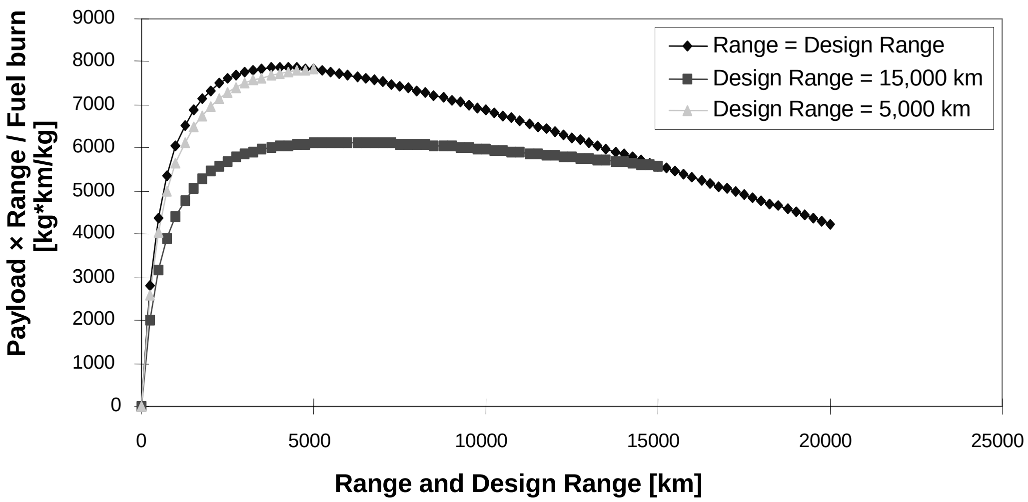

Figure 6. Variation of payload fuel efficiency with range and design range: swept wing kerosene-fuelled aircraft (from Green et al. (2005), arranged by Hans Schnieder (2006))

As shown in Figure 6, the payload fuel efficiency of an aircraft designed for 5000 km on a 5000 km leg would exceed the one of an aircraft designed for 15,000 km by almost 30 %. Of course, this number cannot be generalised in real operations, as aircraft cannot be designed specifically for each needed range, neither for each seat capacity (which is optimised, too, in Figure 6).

4.4 *Impact of TSO on the atmosphere*

In addition to the smaller quantity of emissions, TSO would lead to emissions at lower altitudes compared to single stages. Concerning nitrogen oxides, this might reduce the radiative forcing of such operations. In terms of condensations trails, the answer remains uncertain, as their radiative forcing does not only depend on the altitude, but also on latitude, season and daytime of a flight. Also, their radiative forcing has not yet been evaluated concludingly.

At low altitudes, especially beneath the atmospheric mixing height (~ 3000 ft), high thrust levels at takeoff bring about high NO_x emissions. Requirements from local authorities might limit the traffic or induce design tradeoffs that lead to a higher fuel consumption in cruise flight, but lower NO_x emission indices at takeoff. This would adulterate the initial benefit of TSO in terms of atmospheric impact. A profound assessment of the benefit of TSO for climate change would presume the integration of a reliable atmospheric model or metric in the loop.

4.5 *Operational involvements and economic interest of TSO*

The potential fuel savings presented in chapters 4.1 to 4.3 are theoretical. Several aspects would counteract the benefit of TSO:

- Availability of appropriate airports: Even if an airport was available near the mid-range of a certain route, it is not sure it would be able to handle additional traffic, and that it has the necessary infrastructure (runway strength, fuel supply, navigation aids etc.).
- Maintenance cost due to the higher number of flight cycles
- Additional landing and takeoff cycles affecting local air quality (see 4.4) and noise concerns, especially important at busy airports
- Organisational effort for airlines: crew management, airline subsidies at mid-way airports
- Less flexibility for airlines to choose routes, if aircraft are designed to lower ranges
- Value of time for the passenger: A full landing and takeoff cycle with refuelling takes one to two hours, which might not be acceptable for many passengers, those with children, the old and those paying high ticket prices (business passengers).

The overall economic interest of TSO, justifying the effort of severe modifications of the aviation system, is impacted by all of the aspects mentioned above. TSO are interesting and applicable on specific routes only, but cannot be considered a generally fuel-reducing measure today. An expansion of such operations would presume substantial adaptations in the aviation infrastructure, especially at airports. The overall benefit of TSO depends essentially on the fuel price.

5 SUMMARY AND CONCLUSION

A methodology to consider the atmospheric impact in aircraft design was presented. Two-stage operations illustrated the interest in a systemic view of aviation in this regard. The approach highlighted the discrepancy between purely theoretical considerations and real flight operations.

For the evaluation of the benefit of a new approach in aircraft design and operations in terms of climate change, it is necessary to have a good overview of both the different stakeholders of aviation and the impact of aircraft engine emissions on the atmosphere. The methodology presented here is an approach to allowing for the equitable consideration of aircraft design, market requirements, operational issues and the atmospheric impact. The interaction between aircraft design and atmospheric impact can then be treated not only "bottom up", but as a fully integrated analysis and optimisation loop.

Increasing the complexity of the studied system and the required competences – from aircraft engineering to atmospheric sciences – takes its toll on the precision of results. In order to get realistic and meaningful conclusions, not only are comprehensive methods needed, but also scientific exchange between the respective specialists' communities. Then the correctness of conclusions – within a given precision – can be reasonably assured. The approach presented here proposes a methodological platform for such an integration of both aircraft engineering and atmospheric sciences.

REFERENCES

Lufthansa, 2006: *Balance – Das Wichtigste zum Thema Nachhaltigkeit*. Company report, Frankfurt, Germany, 82 pp.

Penner, J., D.H. Lister, D.J. Griggs, D.J. Dokken and M. McFarland (eds.): *Aviation and the Global Atmosphere*. A Special Report of IPCC Working Groups I and III. Published for the Intergovernmental Panel of Climate Change. Cambridge University Press, Cambridge, United Kingdom, 373 pp.

Egelhofer, R., in press: *Reduzierung des durch Luftverkehr verursachten Atmosphärenschadens durch ganzheitliche Betrachtung im Flugzeugvorentwurf*. Conference Proceedings of the German Aerospace Congress 2005, Vol. III, DGLR-2005-016. Deutsche Gesellschaft für Luft- und Raumfahrt, Friedrichshafen, Germany, 10 pp.

Green, J., 2005: *Air Travel – Greener by Design. Mitigating the Environmental Impact of Aviation: Opportunities and Priorities*. Report of the Greener by Design Science and Technology Sub-Group. Royal Aeronautical Society, London, United Kingdom, 64 pp.

Schnieder, H., 2006: Personal communication.

Operational impacts of trajectory adjustments to avoid ice supersaturated regions

V. Williams[*], R. B. Noland
Centre for Transport Studies, Imperial College London, UK

R. Toumi
Space and Atmospheric Research Group, Imperial College London, UK

Keywords: Aviation, contrail formation, climate, mitigation

ABSTRACT: Contrails and the cirrus clouds they form may have a climate impact as large as that of the CO_2 emitted by aircraft. One opportunity for reducing the climate impact of aviation could be offered by in-flight adjustments to the flight profile to avoid regions of ice super-saturated air, to prevent the formation of contrails.

We explore the potential operational impacts of such a policy, including the consequences for air traffic management and the impact on emissions. The fast-time air traffic simulator RAMSPlus is used to assess the feasibility of such an approach in areas with high air traffic density. The simulations use a 1-day traffic sample for the UK to test the possible disruption associated with an imposed contrail avoidance zone with a diameter of 150 nautical miles and thickness of 1800 ft situated in the South East region. Three altitudes for the base of the contrail avoidance zone are considered. This extended abstract considers the impact of zone avoidance on three sample flights.

1 INTRODUCTION

Contrails, and particularly the cirrus clouds which they can spread to form, are believed to be a significant factor in aviation's contribution to global climate change.

The scope for technological measures to reduce contrail formation is limited. Options to manipulate the radiative properties of the cirrus cloud formed may be possible (for example by increasing the number of condensation nuclei in the exhaust, to result in more, smaller particles in the contrail), but at present the radiative consequences of such a measure are not well understood and the impact on climate may well be increased. A more feasible alternative is to divert aircraft to avoid regions in which persistent contrails form. For many years, this has been a strategy to preserve the secrecy of military aircraft movements, but it may also have benefits for climate.

Fixed monthly altitude restrictions have been identified from the atmospheric conditions in Western European airspace and air traffic simulations used to assess the potential impacts on both fuel burn and on airspace (Williams et al., 2002). A follow-on study took into account shorter term variability, using an efficiency based criteria to simulate application of altitude restrictions selected every six hours based on atmospheric conditions in order to minimize the fuel burn penalties (Williams and Noland, 2005). Both these studies were based on coarse (2.5°x2.5°) resolution global atmospheric data and considered the application of maximum cruise altitudes across a large area (the European 5 States region). Recent analysis of radiosonde data to identify ice-supersaturated regions has suggested the mean vertical extent of these layers is 560m (Spichtinger et al., 2003). It has been suggested that the thinness of these layers would provide scope for in flight adjustments to cruise altitudes to avoid contrail formation in conjunction with a free-flight policy (Mannstein et al., 2005). By incorporating real time information on local atmospheric conditions, this approach would provide much more targeted adjustments in cruise altitude. This would reduce the fuel burn penalty as only unnecessary altitude adjustments would be made, and the altitude change would be mini-

[*] *Corresponding author:* Victoria Williams, Centre for Transport Studies, Department of Civil and Environmental Engineering, Imperial College London, Exhibition Road, London, SW7 2AZ, UK. Email: v.williams@imperial.ac.uk

mised. However, from an airspace management perspective, the policy becomes more complex than the monthly shifting region-wide maximum cruise altitude proposed in (Williams et al., 2002) or even the variable policy in (Williams and Noland, 2005). These would both allow a limited number of cruise altitude restriction scenarios to be applied and airspace configuration to be appropriately designed for each. However, new air traffic control technologies expected in the future could decrease the difficulties associated with real time avoidance of contrail formation conditions (Williams et al., 2006).

While flight adjustments to filed flight plans are not uncommon, for example to avoid convective weather systems, a scheme of this nature for contrail avoidance would place an additional planning and monitoring burden on both pilots and controllers. Some incentive-based scheme may also be required for contrail avoidance to be effective. Airlines have always had an incentive to minimise fuel consumption in order to keep costs low and to increase payload and range. Increases in fuel costs have enhanced this pressure. Any policy to avoid contrail formation is likely to require diversion from the fuel-optimising preferred route. The costs to airlines would be further increased if diversions were large enough to significantly impact on journey time. If the onus were placed on the pilot to inform the controller of contrail formation conditions, then some incentive based scheme such that the cost of contrail formation exceeded the fuel and time penalty would be required. In the future, aircraft-based detection and reporting of contrail formation conditions could be automated by linking humidity and temperature sensors to datalink systems, thereby transmitting atmospheric data along with aircraft position and intent information to the air traffic controller and to other aircraft in the vicinity.

Increasing cruise altitudes to fly above the contrail formation layer may also offer some benefit but there are caveats. One is that some existing aircraft would not be capable of achieving these altitudes; for those that are, additional fuel is required in the climb phase to achieve higher altitude. Clearly, there would also be some contrail and cirrus cloud formation from aircraft flying through ice-supersaturated layers during their climb to higher altitudes. Of greater significance for very high altitude flights is the long lifetime of water vapour in the lower stratosphere. Although, in this region, condensation will not occur, there will be a radiative impact from the accumulation of water in its vapour form.

2 METHOD

This study uses the RAMS fast-time simulation model to identify some of the characteristics associated with the avoidance of contrail formation regions. We assume that contrail formation regions are sufficiently stable to be designated as restricted airspace regions, with the designated region allowed to persist. This simulation approach addresses both the changes in fuel burn and NO_x emissions from the altered flight trajectories and the airspace complexity issues associated with diverting traffic into or out of highly congested routes to avoid contrail formation regions. It does not address the additional pilot or controller workload associated with monitoring the changes in atmospheric conditions and identifying the extent of the contrail formation region to be designated for avoidance.

The contrail formation region is defined within the model as restricted use airspace, exactly analogous to the definition of military airspace. The region is centred over the heavily trafficked south east region of the UK and is shown in Figure 1, which also shows the flight routes for the control traffic sample. Three altitude scenarios were considered. The thickness of the avoidance region was set at 1800 ft and the base level is at 24000 ft, 29100 ft and 37200 ft for the LOW, MID and HIGH simulations respectively. These altitudes are consistent with radiosonde observations (Spichtinger et al., 2003). The horizontal extent of the avoidance region was 150 nautical miles, consistent with aircraft observations of path length through ice supersaturated air (Gierens and Spichtinger, 2000). As the simulator requires airspace to be defined as a set corners joined by straight boundaries, the circular avoidance zone is approximated as a 16-sided polygon. Three avoidance scenarios are considered for each altitude zone.

3 TRAJECTORY CHANGES FOR SAMPLE FLIGHTS

For this initial presentation of results, 3 flights were selected for analysis. This allows the trajectory adjustments imposed by the simulator to be explored. Figure 2 shows the trajectory adjustments tested for each flight. Changes in emissions are summarised in Table 1.

3.1 *Flight 1: Tenerife – Nottingham East Midlands*

In the control simulation, this Airbus A320 aircraft crosses the contrail avoidance area at FL250, so travels through the low avoidance zone. The aircraft enters UK airspace to the South of the avoidance zone, flying North East before completing a positioning manoeuvre to approach the runway at Nottingham East Midlands from the North West (Fig 2, top). For the AROUND scenario, the diversion in the simulation model is imposed so as to return the aircraft to its original planned route at the earliest opportunity (i.e. to the first navaid on the original route falling outside of the avoidance zone), rather than to optimise the trajectory. As such, the scenario gives an upper limit on the time and emission increases incurred by flying around the region. These penalties could be reduced with better routing optimisation. Similarly, in the UNDER scenario the aircraft returns to its initial cruise altitude on leaving the avoidance zone, shortly before beginning descent. Further simulations are required to determine whether the journey time and emissions penalties would be reduced by maintaining the lower cruise altitude on exit from the avoidance zone.

At these low altitudes for this aircraft type, diverting the aircraft over the avoidance zone increases the cruise speed and so reduces the journey time. It also reduces the fuel burn rate.

3.2 *Flight 2:Athens – Manchester*

This Boeing 737 flight crosses the avoidance zone from South East to North West in the control simulation. At a cruise altitude of 30,000 ft. In the UNDER scenario, the aircraft returns to its initial altitude before immediately beginning its descent to the airport. This requires an additional fuel burn in the climb phase without the benefit of greater efficiency at cruise, so emissions will be higher than if the aircraft were allowed to continue at the lowered avoidance altitude before descending. The AROUND scenario for this flight route provides a more realistic diversion than that offered for Flight 1, with the avoidance trajectory closer to the minimum distance required to avoid the zone, leading to reduced penalties for journey time and emissions. For Flight 2, diverting over the contrail zone reduces the cruise speed, increasing journey time and emissions.

3.3 *Flight 3: Chicago – Frankfurt*

Flight 3 is an over flight, crossing the UK in the cruise phase of flight, en route from Chicago to Frankfurt. The aircraft is an Airbus A330. Journey time penalties for diverting either above or below the avoidance zone are negligible, although emissions increase in both cases. Diverting around the contrail zone yields a journey time penalty of almost 10 minutes, although as with Flight 1, this represents an upper limit; better routing optimisation could reduce this substantially.

Table 1 Summary of changes in journey time and emissions of CO_2 and NO_x. Percent emissions changes are shown as a fraction of the total flight.

Flight	Diversion	Journey time	CO_2	NO_x
1 LOW	Under	+35 s	+0.2 %	+0.5 %
Tenerife – Notting-	Over	-19 s	-0.1 %	+0.1 %
ham East Midlands	Around	+296 s	+2.0 %	+1.7 %
2 MID	Under	+0 s	+0.1 %	+0.3 %
Athens - Manchester	Over	+24 s	+0.05 %	+0.2 %
	Around	+112 s	+1.1 %	+0.9 %
3 HIGH	Under	+0 s	+0.5 %	+1.0 %
Chicago – Frankfurt	Over	+0 s	+0.4 %	+0.6 %
	Around	+576 s	+2.8 %	+3.3 %

4 DISCUSSION

4.1 *Technological developments*

The technological requirements for monitoring and mapping the contrail formation regions, and particularly for forecasting their future positions, are considerable, but systems could be based on currently available technology. Best results for contrail reduction would be achieved using accurate global satellite observations with high horizontal and vertical resolution of relative humidity and temperature, but for humidity particularly, this data is not currently available. Radiosonde data can provide very detailed local profiles, but the spatial extent of a contrail formation cell could not be accurately determined in this way. One approach would combine data from a range of sources, including satellites, ground based observations and on-board instrumentation. Real time satellite photography could also be potentially used as an identifier of contrail formation regions, when coupled with traffic data and aircraft observations to identify the altitudes at which formation was occurring. These approaches, or a combination of them, would not provide complete contrail avoidance, but would allow subsequent aircraft on the same route to avoid contrail formation, thereby reducing the total climate impact.

4.2 *Innovative airspace and ATM concepts*

This approach to assessing operational impacts of an adaptive contrail formation policy does not include innovative concepts in airspace design that are currently being researched. One such innovative approach is the introduction of dedicated ‘highways’ for air traffic, which would contain several lanes of air traffic travelling along parallel defined routes defined to be clear from other traffic, with aircraft given responsibility for maintaining separation. These highways would be designed to reduce en-route delay on highly trafficked routes by having fixed access and departure points and procedures and strict constraints on the aircraft permitted to use the routes. These highways would be dynamically designed to optimise performance based on fuel efficiency and/or journey time, but there is additional scope to reduce the environmental impact on these routes by including an assessment of contrail formation conditions in the selection of the highway route.

Other innovative research areas currently being explored, such as improved weather visualisation systems for controllers, could also be adapted to facilitate contrail avoidance (Williams et al., 2006).

5 CONCLUSIONS

These assessments of the impacts of avoiding a contrail formation zone apply only to the three flights described. Even for the same size avoidance zone, a different position relative to the original flight trajectory would lead to different impacts of avoidance.

For each of the three sample flights described here, diversion around the contail avoidance zone leads to greater time and emissions increases than diversion above or below the zone. This preliminary analysis of the response of sample flights to the diversions imposed by the simulation model has informed the design process for future work to address the system wide implications of such a policy. Diverting around the avoidance zone imposes unrealistic flight trajectories and overestimates the impacts of diversion; it is a worst-case scenario. Manual specification of preferred avoidance routes could address this, but would be impractical for analysis of large traffic samples.

One issue yet to be confirmed is the use of appropriate indicators of the impacts of diversion when considering impacts on a system wide basis. Here, we have used percent changes in emissions relative to the full flight trajectory (assuming great circle routes outside UK airspace). Any measure of the impact will be indicative of the simulated situation only; avoidance trajectories and their impacts will be sensitive to the location of the avoidance zone, and to the traffic sample.

REFERENCES

Gierens, K. and P. Spichtinger, 2000, On the size distribution of ice-supersaturated regions in the upper troposphere and lowermost stratosphere, Annales Geophysicae-Atmospheres Hydrospheres and Space Sciences 18 (4), 499-504.

Mannstein, H., P. Spichtinger and K. Gierens, 2005, A note on how to avoid contrail cirrus, Transportation Research Part D: Transport and Environment 10 421-426.

Spichtinger, P., K. Gierens, U. Leiterer and H. Dier, 2003, Ice supersaturation in the tropopause region over Lindenberg, Germany, Meteorologische Zeitschrift 12 (3), 143-156.

Williams, V., R. B. Noland and R. Toumi, 2002, Reducing the climate change impacts of aviation by restricting cruise altitudes, Transportation Research Part D: Transport and Environment 7 (6), 451-464.

Williams, V. and R. B. Noland, 2005, Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation, Transportation Research Part D: Transport and Environment 10 (4), 269-280.

Williams, V., A. Majumdar, R. B. Noland, W. Ochieng and R. Toumi, 2006, ITS in the Sky - Scope for Reducing Environmental Impacts of Aviation with Innovative Air Traffic Management Technologies, Intelligent Transport Systems World Congress, London.

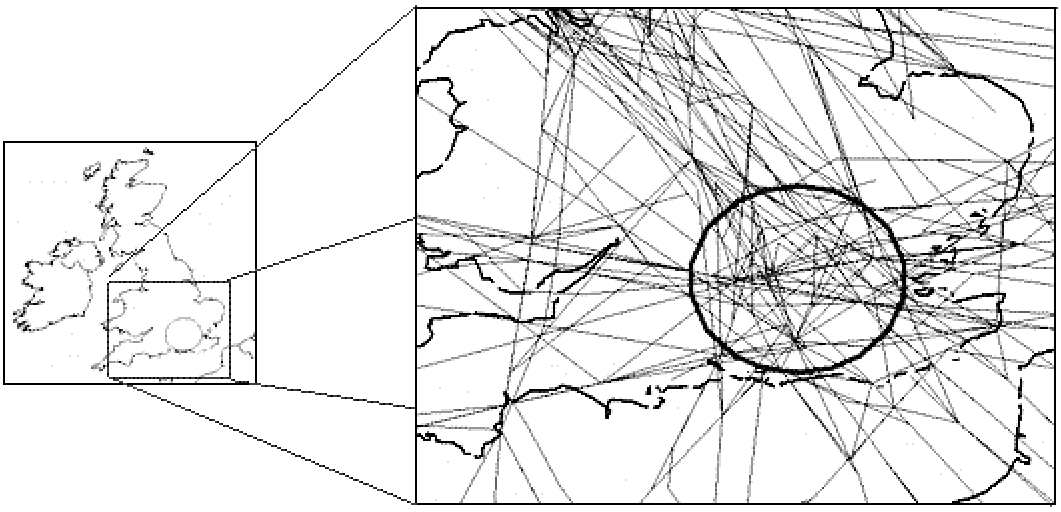

Figure 1 The location of the contrail avoidance region imposed and flight routes in the control traffic sample.

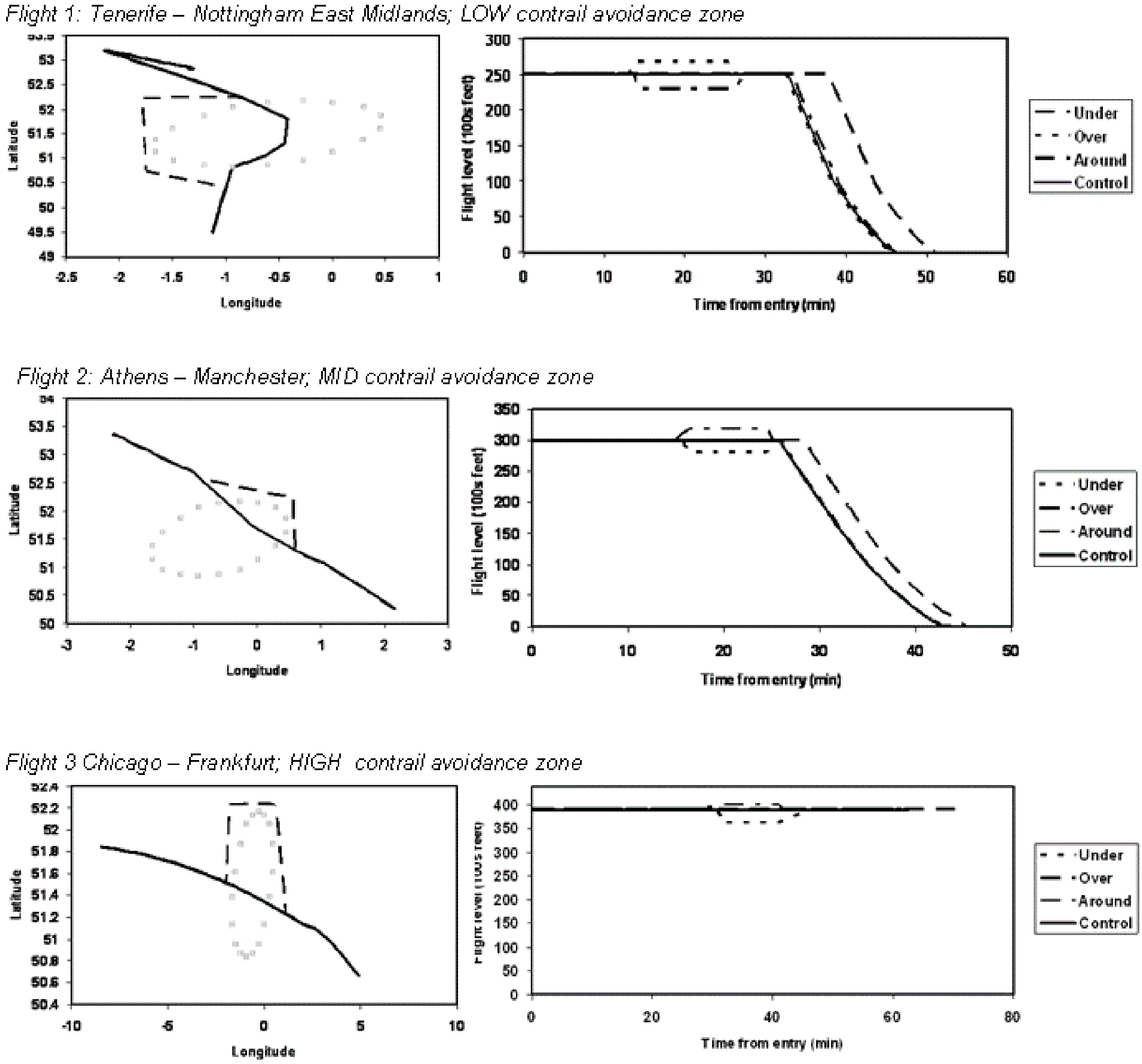

Figure 2 Flight routes (left) and profiles (right) for the three sample flights showing the diversion under, over and around the contrail avoidance zone.