Contrail avoidance in the aircraft design process

F. Noppel and R. Singh
School of Engineering
Cranfield University
Bedfordshire, UK

ABSTRACT

As aviation is one of the fastest growing industrial sectors world wide, air-traffic emissions are projected to increase their stake in the contribution to global warming. According to studies, both carbon dioxide and contrails are the principal air-traffic pollutants, whereas the impact from contrails in terms of radiative forcing is possibly larger than that of all other air-traffic pollutants combined. New regulations with the objective of mitigating contrail occurrences might cause a change in the design requirements of aircraft. In light of this, a method considering contrail formation during the aircraft design process is presented in this paper. Aircraft performance and optimisation is carried out with NASA's flight optimisation system. Combining historical meteorological data with air-traffic data enables an assessment regarding contrail formation. As an example, a particular aircraft type in terms of range, speed and payload is optimised for minimum block fuel consumption considering different altitudes. The change in contrail formation in terms of contrail-km formed is calculated. The results suggest that if aircraft of the considered class were designed for higher altitudes, contrail occurrences would diminish slightly at a non-negligible fuel burn penalty.

1.0 INTRODUCTION

The importance of air-traffic pollutants in the global climate, especially in the light of projected passenger numbers, is repeatedly stressed in aviation assessment reports.

In a recent report by the Intergovernmental Panel on Climate Change[1], persistent contrails and so called contrail cirrus clouds, which are persistent contrails that spread in a highly ice-supersaturated environment, have been identified as possibly the principle contributors to the total radiative forcing, a metric for the steady-state response of the mean global temperature of a particular pollutant[2], from commercial air-traffic. Although with some uncertainty at the current level of understanding, there is the possibility that the radiative forcing from persistent contrails and contrail cirrus combined is 70·4% of the total radiative forcing from aviation, despite their much shorter life time than that of other pollutants such as carbon dioxide.

In general, aircraft are designed to serve a particular market and to maximise their earning capacity. Factors driving the aircraft design are such as payload, range, the prevailing air-traffic infrastructure, and the aircraft's competitive advantage in terms of economical performance. The design process typically yields a configuration that meets the design requirements within the constraints imposed by regulations regarding safety, performance, and environmental impact.

As in particular the environmental impact of persistent contrails and contrail cirrus is increasingly emphasised, regulations might be introduced with the objective of the avoidance of persistent contrails, which would possibly imply the avoidance of contrail cirrus as well. These regulations will either affect the current aircraft fleet, e.g. how aircraft are operated, or influence the design of next generation aircraft. Airlines and air traffic management would probably have to deal with the former approach, whereas the manufacturer would have to respond to the latter as it will cause a shift in the aircraft design requirements.

The formation of persistent contrails is dependent on many factors, such as chemical reactions and aerodynamics in the aircraft wake, the state of the atmosphere within the flight corridors, and engine technology, just to name a few. Due to this complexity,

Paper No. 3285. Manuscript received 10 March 2008, revised 24 July 2008, accepted 12 August 2008.

https://doi.org/10.1017/S0001924000002700 Published online by Cambridge University Press

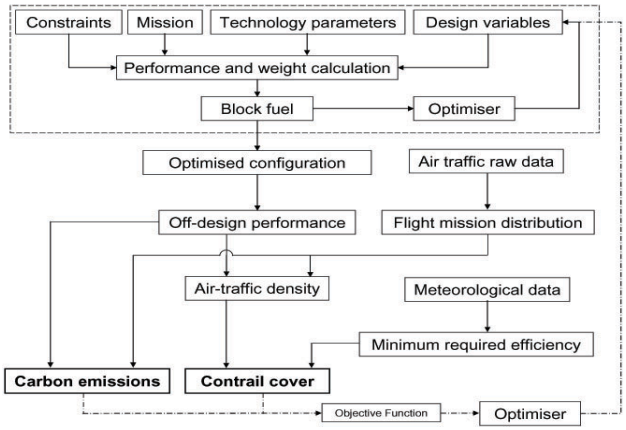


Figure 1. Layout of aircraft design process where contrail formation is taken into account. The part covered by NASA's flight optimisation system is framed with a dashed line.

contrail avoidance becomes a challenging task. One approach could be the temporary restriction of flight corridors as described in Ref. 3. The impact on fuel additives on contrail formation is discussed in Ref. 4, where it is suggested that they are not a viable solution. More approaches are summarised and proposed in Refs 5 and 6; it is now to find the most suitable one.

In Ref. 7, a parametric study demonstrates that contrail occurrences and hence the associated radiative forcing could be mitigated if global air-traffic took place at lower altitudes. However, considering the current global aircraft fleet, shifting air corridors would imply an increase in fuel consumption, resulting from the dependency of aircraft and engine performance on cruise altitude. The additional fuel burn inevitably leads to larger quantities of greenhouse gas emissions, which is not desirable because of the associated environmental impact.

As both fuel consumption and contrail formation of a particular aircraft are dependent on cruise altitude, aircraft optimisation in terms of cruise altitude could yield an acceptable compromise between fuel burn and contrail formation once decided how to position an aircraft in the market in terms of payload, range and cruise speed.

This study addresses contrail avoidance and how the design processes could be adapted if new requirements were to be met and no alternative technology was available to avoid contrail formation. The methodology is demonstrated assessing contrail formation and fuel consumption of a particular aircraft class considering different cruise altitude scenarios.

2.0 METHODOLOGY

Fundamentally, the methodology can be broken down into two parts. One part covers the prediction and optimisation of the aircraft configuration depending on design variables, technology parameters, and mission requirements. Combining the calculated performance with air traffic data, the global fuel consumption resulting from a fleet of the considered aircraft configuration can be calculated. The second part includes the calculation of the environmental impact from contrails on a global scale. As the calculation of the radiative forcing from contrails is time consuming and requires sophisticated software such as global circulation models or radiative transfer models[8,9], this study considers the amount of persistent contrails formed instead. It is measured in contrail-km, which is the cumulative sum of the fractions of flight paths where the formation of persistent contrails is facilitated, which is realised by combining air traffic data with historical meteorological data. A representation of the overall procedure is given in Fig. 1.

NASA's flight optimisation system (FLOPS) was used for performance calculation and multidisciplinary optimisation of a particular engine and aircraft configuration. The code computes airframe weight, airframe aerodynamics, engine weight and engine performance according to the airframe and engine related parameters and design variables, from which the block fuel is calculated. The part covered by FLOPS is framed with a dashed line in Fig. 1.

Ideally, optimisation of the aircraft configuration is carried out considering contrail formation already during the optimisation process. The figures of merit, block fuel and contrails, would then be combined in the objective function, represented by the dashed arrow in Fig. 1. In this study, the aircraft configuration was optimised for minimum block fuel for a particular altitude, and the resulting configuration was then subsequently assessed in terms of persistent contrail formation. The aircraft design variables were wing area, thickness to chord ratio and sweep angle; engine design variables were bypass ratio and take-off thrust.

The design point mission was defined by range, cruise speed in terms of true air speed, and initial cruise altitude. Block fuel was calculated considering continuous climb during cruise. Cruise altitude was restricted to a certain altitude band for both the design point and off-design point mission. Mission requirements in terms of landing and take off field length, rate of climb/descent and approach speed were taken into account according to the FAA regulations.

Air-traffic density, defined as the sum of distances flown by aircraft within a certain volume or area within a given time period, was calculated from a database provided by the Department of Air Transport at Cranfield University. The database holds information of national and international scheduled commercial flights. As only the air-traffic density that would result from the considered aircraft class is of interest when calculating contrail formation and fuel burn on a global scale, the data were filtered by specifying minimum and maximum number of seats. Knowing destination and departure point for each flight, the flight routes were approximated in three dimensions assuming the flight route along the great circles between the departure and destination points. Cruise altitudes, climb and descent fractions were obtained from range/payload performance tables, which were generated utilising the off-design capabilities of FLOPS. The diurnal variability in air-traffic was taken into account. Knowing departure time and destination time for each flight, four air-traffic density maps were computed for each altitude scenario. The resulting maps are shown in Fig. 2, covering the time periods 0-6h, 6-12h, 12-18h, and 18-24h (Universal Time).

Regions that facilitate the formation of contrails are primarily determined by local ice-supersaturation levels, altitude, ambient temperature and engine efficiency. Operational weather analysis data from the MetOffice unified model of the year 2005 was evaluated regarding contrail formation applying the Schmidt-Appleman criterion[10]. It determines whether contrail formation is facilitated or not if ambient temperature and humidity, as well as engine efficiency are known. If the Schmidt-Appleman criterion is met and the atmosphere is ice supersaturated, persistent contrail formation is facilitated. The data contain information regarding temperature and relative humidity in six-hour intervals on a global grid with 21 pressure levels. As the engine efficiency is the only variable aircraft related parameter in the Schmidt-Appleman criterion, the minimum engine efficiency required for contrail formation was calculated in the first instance. Because this calculation is time consuming, it was advantageous to perform it only once and use the results for all altitude scenarios. Figure 3 shows the time averaged probability for persistent contrail formation calculated from 2005 operational weather analysis data assuming the overall engine efficiency assumed 40%. Persistent contrail formation is most likely to occur over tropical regions at altitudes equating to 33,000-45,000ft (10,058-13,716m).

In the second instance, the amount of persistent contrails formed was calculated in terms of contrail-km for each six hour interval. As aircraft optimised for different altitudes cruise with different overall

https://doi.org/10.1017/S0001924000002700 Published online by Cambridge University Press

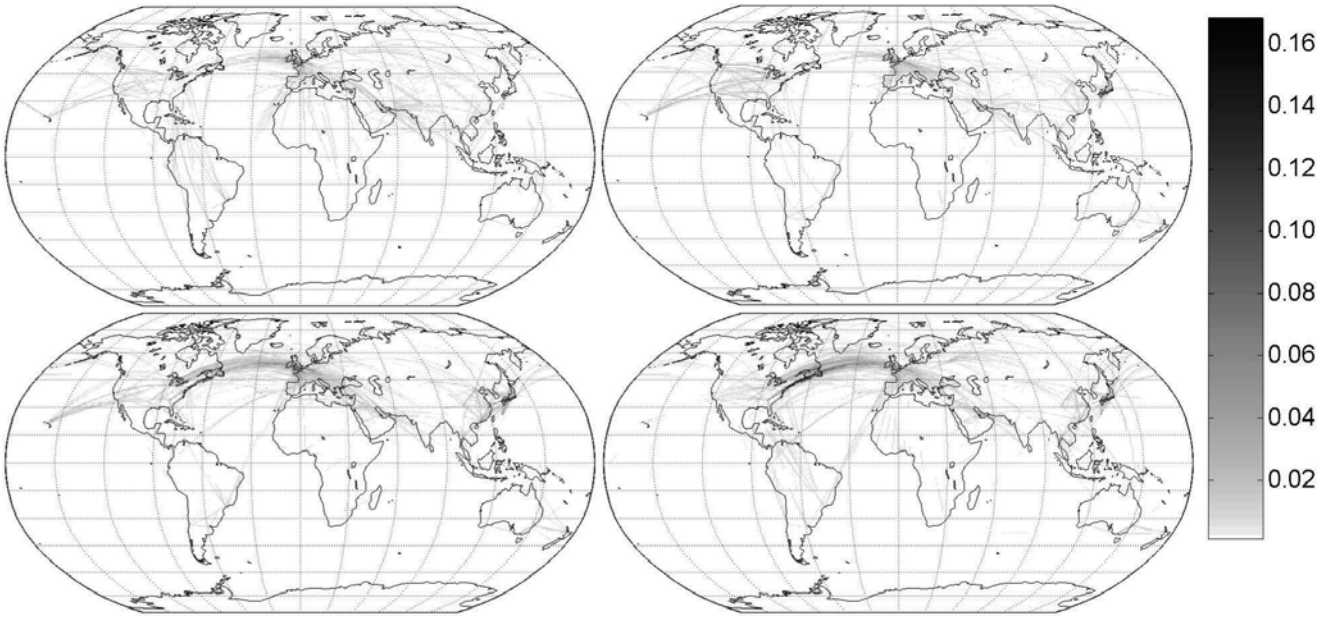


Figure 2. The cumulative air traffic density over all altitudes in km/(km^2/hour) considering 200-250 seater aircraft only. 00-06h (top left), 06-12h (top right), 12-18h (bottom left), 18-24h (bottom right).

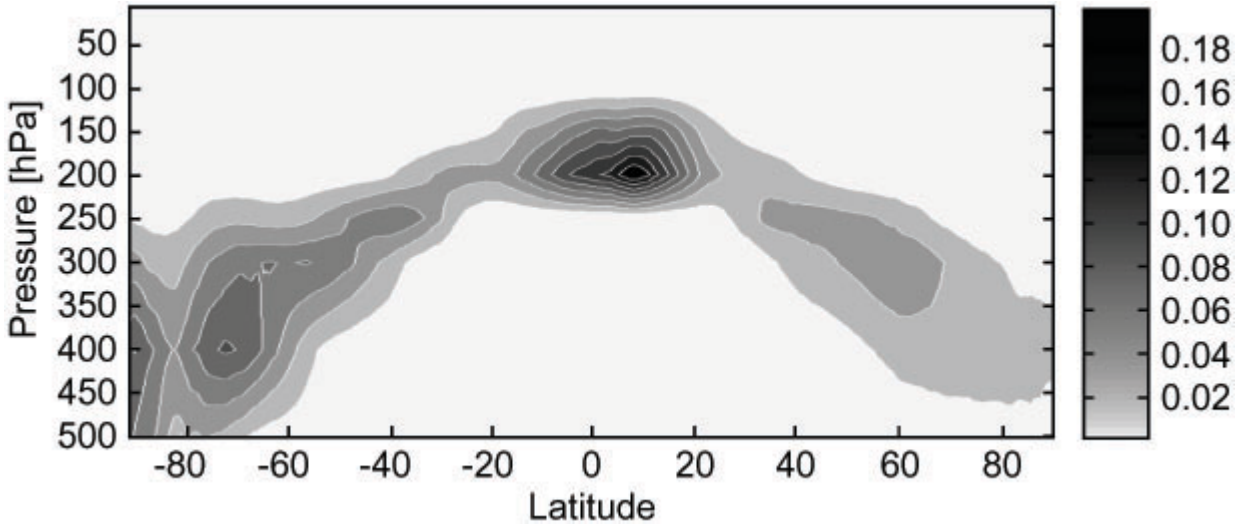


Figure 3. Time averaged probability for persistent contrail formation calculated from 2005 operational weather analysis data (overall engine efficiency assumed 40%).

efficiencies, the effect of cruise efficiency on persistent contrail formation was taken into account for each altitude scenario.

The aircraft class taken into account in this study has a maximum range of 8,000 nm (14,816km) and a cruise speed of 255ms^{-1} (about Mach 0·86 at 34,000ft). With a maximum payload that represents the weight of about 250 passengers, the selected aircraft class represents a modern long haul, mid-size commercial transport aircraft. The journey length distribution of flights with aircraft between 200-250 seats is given in Fig. 4. It can be seen that most of the flights occur for short legs.

Best estimates for future engine and aircraft related parameters were made accessible by industry and could be derived from information available in the public domain. The altitude scenarios were chosen to be in 1,000ft (305m) steps with 34,000ft (10·36km) as baseline. Airframe technology related parameters, determining primarily material weight and aerodynamic wing performance, and engine related technology parameters such as maximum turbine entry temperature, overall pressure ratio, fan pressure ratio or parameters related to the mechanical integrity of the turbomachinery, were held fixed in all altitude scenarios.

https://doi.org/10.1017/S0001924000002700 Published online by Cambridge University Press

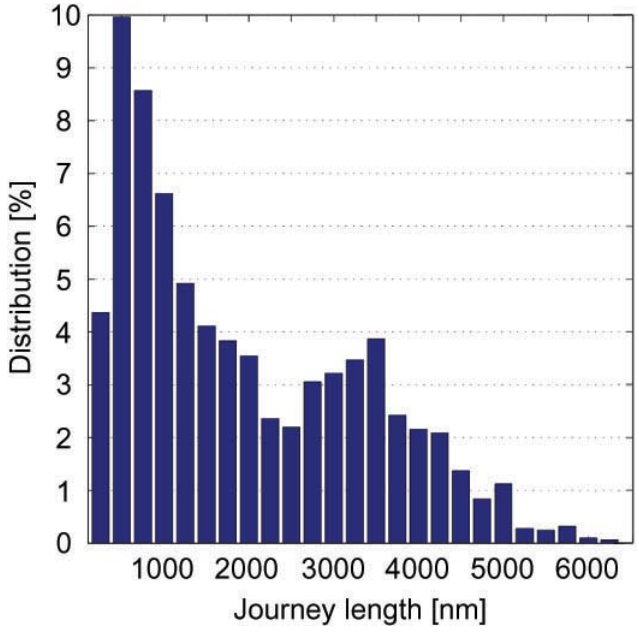


Figure 4. Journey length distribution for 200-250-seat aircraft.

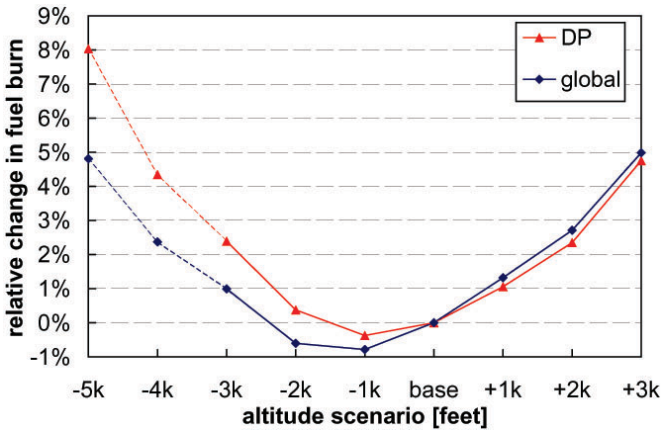


Figure 5. Fuel burn penalty relative to baseline configuration (34,000ft) at the design point (DP) and on a global scale (global).

3.0 RESULTS

Figure 5 shows the change in fuel consumption relative to the baseline configuration for both the design mission and on a global scale. The block fuel consumption ultimately increases as the aircraft is designed for both lower and higher altitudes. According to the results, the configuration optimised for 31,000ft would consume 2·4% more fuel at its design point than the baseline configuration optimised for 34,000ft. On a global scale, the fuel burn penalty would be 1·0%. The difference in fuel burn compared to the baseline configuration for aircraft designed for 37,000ft is calculated to be 4·8% at the design point, and 5·0% on a global scale.

Figure 6 shows the relative change in the design variables for the different altitude scenarios. Thrust and bypass ratios are calculated at sea level static. The results suggest that the configuration optimised for higher altitudes has higher thrust requirements, larger wing areas, but smaller bypass ratios. The effect is not entirely inversed for a

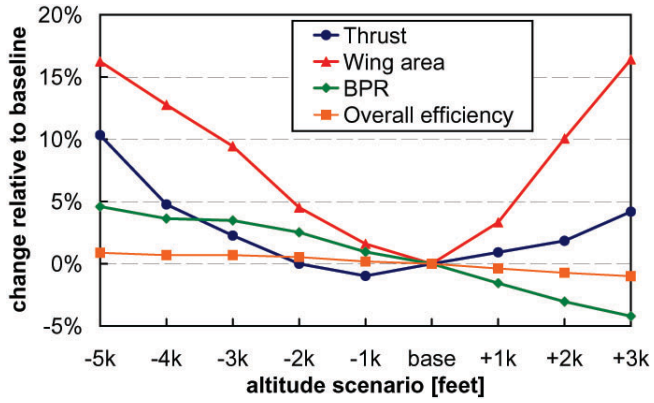


Figure 6. Changes in design variables relative to the baseline configuration (34,000ft).

configuration optimised for lower cruise altitudes. According to the calculations, the optimum bypass ratio is increasing for lower cruise altitudes, thrust requirements would be lower, but the wing area would also be larger.

The aircraft configuration resulting from an optimisation is dependent on various factors. It is, however, mainly affected by the change in air density at higher altitudes, impacting lift, drag and engine performance, and design constraints, such as minimum climb/descent gradient requirements.

The fuel consumption and hence aircraft weight depends primarily on the thrust requirement during cruise and the engine efficiency. At high altitudes, where the air density is lower, higher mass flow rates through the engine are required in order to obtain enough thrust. An ever increasing engine diameter can, however, not be accommodated due to limited space below the pylon, engine weight and increasing nacelle drag. Hence, the engine exit velocity is increased to provide enough thrust, which is achieved through lower bypass ratios. This, in effect, negatively affects the overall aircraft efficiency, driving block fuel consumption.

For lower altitudes, the air is denser than at high altitudes, and hence the air mass flow through the engine is increased. This allows larger bypass ratios without the necessity of very large engine diameters, resulting in better overall engine efficiencies. At low altitudes, however, the higher air density causes an increase of the parasitic drag, impacting fuel consumption.

As deployable aerofoils, such as flaps and slats, were not considered in this study, minimum climb/descent gradient requirements, including one engine off conditions at 1,500ft, at given take-off/approach speeds resulted in wing areas as shown in Fig. 6.

The relative change in persistent contrail formation for each altitude scenario on a global scale, measured in terms of contrail-km, is given in Fig. 7. According to the results, aircraft optimised for lower altitudes tend to cause more contrails, whereas higher cruise altitudes indicate a decrease in contrail formation. According to the results, almost 58·0% more contrails would form for a configuration designed for 31,000ft instead of 34,000ft, and results suggest that 10·1% less contrails would form for a configuration designed for 37,000ft.

The persistence of contrails, and ability to spread to contrail cirrus, is primarily dependent on ambient ice supersaturation. Therefore, the change in contrail occurrences in regions of different levels of ice-supersaturation was calculated, and results are shown in Fig. 8. Configurations optimised for lower altitudes would particularly increase contrail formation under relatively high ice-supersaturated conditions, possibly giving rise to contrail cirrus occurrences.

https://doi.org/10.1017/S0001924000002700 Published online by Cambridge University Press

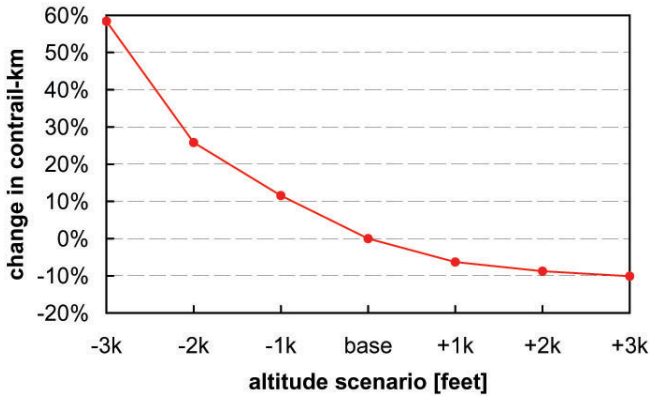


Figure 7. Change in persistent contrail formation in km contrails relative to baseline configuration (34,000ft).

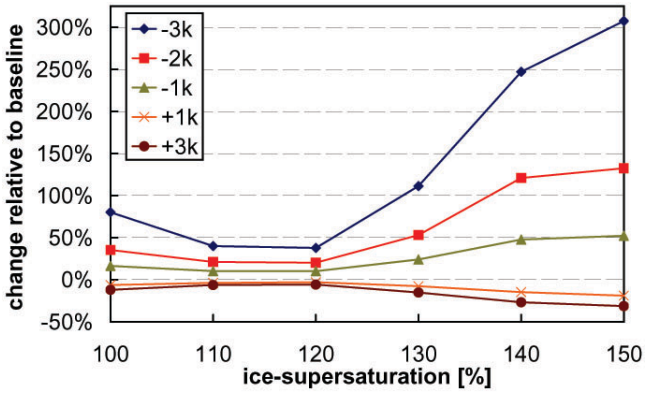


Figure 8. Contrail formation in km contrails relative to baseline configuration (34,000ft) for different levels of ice-supersaturation.

4.0 DISCUSSION

The results suggest that aircraft of the considered aircraft class designed for lower altitudes would produce more persistent contrails and would ultimately consume more fuel. If designed for higher altitudes, the fuel burn would also be higher but less persistent contrails, 10·1% according to the results, would be produced. This would imply that, unless aircraft could be designed for even higher or much lower altitudes without considerable fuel burn penalty, occurrences of persistent contrails could only be reduced marginally through aircraft design, leading to compromises in terms of fuel burn.

Results in this study are in contradiction with other studies[7,8], where results suggest that cruising at lower altitudes would reduce contrail occurrences. The difference in this study is that only one particular aircraft class and its associated contrail occurrences is considered. There is an altitude at which contrails are most likely to form, and aircraft can either cruise above or below it. As the optimum cruise altitude in terms of fuel consumption is dependent on various parameters, such as payload, cruise speed and technology, individual optimisation of aircraft for contrail avoidance would shift the air-traffic toward altitudes where contrail formation is mitigated. This would not necessarily imply that all aircraft would be designed for either higher or lower altitudes. If contrail formation is most likely to occur for a particular altitude, then contrails could be avoided by designing aircraft for an altitude where contrail formation is minimised. Depending on the design requirements, the technology and where the aircraft are expected to operate, this could be for both higher or lower altitudes compared to current designs.

Further reducing cruise altitude of the aircraft class considered in this study would probably make sense in terms of contrail formation, because for much lower altitudes contrail occurrences would diminish again due to higher ambient temperatures. However, the fuel burn penalty would be over proportionally larger. New technologies, such as unducted fans or compromises in terms of aircraft speed, could alleviate the fuel burn penalty.

The objective, to create a design tool to estimate contrail formation during the design process of aircraft, was met. However, several approximations impose limitations: it has to be taken into account that contrails and carbon dioxide are not the only pollutants from air traffic. The environmental impact of other emissions, such as NO_x, varies with altitude and would have to be considered as part of a more integral approach[10]. Also, a metric for the environmental impact from contrails other than contrails formed would be required for a more adequate assessment.

REFERENCES

1. SOLOMON, S., QIN, D., MANNING, M., CHEN, Z., MARQUIS, M., AVERYT, K.B., M.,T. and L.M.H. *Climate Change 2007: The Physical Science Basis*, 2007, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Cambridge University Press, New York, USA.
2. HANSEN, J., SATO, M. and RUEDY, R. Radiative forcing climate response, *J Geophysical Research*, March 1997, **102**, (D6), pp 6831–6864.
3. WILLIAMS, V. and NOLAND, R.B. Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation, *Transportation Research D*, 2005, **10**, (4), pp 169–280.
4. GIERENS, K. Are fuel additives a viable contrail mitigation option? *Atmospheric Environment*, 2007, **41**, 10.1016, pp 4548–4552.
5. NOPPEL, F. and SINGH, R. Contrail and cirrus cloud avoidance technology, *J Aircr*, 2007, **44**, (5), pp 1721–1726.
6. GIERENS, K., LIM, L. and ELEFTHERATOS, K. A review on various strategies for contrail avoidance, *Open Atmospheric Science J*, 2008, **2**, pp 1–7.
7. FICHTER, C., MARQUART, S., SAUSEN, R. and LEE, D.S. The impact of cruise altitude on contrails and related radiative forcing, *Meteorologische Zeitschrift*, August 2005, **14**, (4), pp 563–572.
8. RAEDEL, G. and SHINE, K. Radiative forcing by persistent contrails and its dependence on cruise altitudes, *J Geophysical Research*, April 2008, **113**, 10.1029/2007JD009117.
9. SCHUMANN, U. On conditions for contrail formation from aircraft exhausts, *Meteorol Zeitschrift*, February 1996, **5**, pp 4–23.
10. STEVENSON, D.S., DOHERTY, R.M., SANDERSON, M.G. COLLINS, W.J., JOHNSON, C.E. and DERWENT, R.G. Radiative forcing from aircraft NO_x emissions: Mechanisms and seasonal dependence, *J Geophysical Research*, 2004, **109**.

https://doi.org/10.1017/S0001924000002700 Published online by Cambridge University Press