TRADE-OFF ANALYSIS OF OPTIONS FOR MITIGATING CLIMATE EFFECTS OF AIRCRAFT INDUCED CLOUDS

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Abstract

It is a little-known fact that not *all* of anthropogenic (i.e. human made) Global Warming is a result of "greenhouse gases." Whereas 98% of anthropogenic Global Warming is the result of emissions of "greenhouse gases" (e.g. CO_2 and methane), the remaining 2% is the result of Aircraft Induced Clouds (AIC) that are generated by jet engines. These high clouds reflect back to Earth approximately 33% of the outgoing "thermal" radiation.

This paper describes the results of a multi-attribute utility analysis to evaluate the potential of alternate technologies and operations to reduce AIC. The analysis identified technologic and operational solutions for each of three processes that result in radiative forcing from AIC: (1) propulsion chemistry that converts aviation fuel to water vapor and soot, (2) clouds physics that converts water vapor and soot into ice-crystals, and (3) radiative forcing physics that absorb the radiation.

The highest utility and lowest design and implementation costs are to flight plan trajectories to minimize cruise flight levels in airspace with atmospheric conditions that are conducive to AIC generation. Other alternatives such as reduced-Sulphur kerosene-based jet fuel, drop-in bio and synthetic fuels, require significant investment to scale production. Options such as jet engine designs to reduce soot emissions, alternate energy sources such as liquid natural gas and liquid hydrogen, and engine and aircraft designs to reduce fuel burn, require significant research and turn-over of the existing fleets. Fuel additives to suppress ice crystal formation and/or change the Radiative Forcing (RF)properties of ice-crystals are still nascent research topics. The implications and limitations are discussed.

Introduction

The aviation industry has a unique opportunity to significantly reduce its Radiative Forcing (RF) contribution to global warming, and stay ahead of the politics, social media, and regulations by minimizing the generation of Aircraft Induced Clouds (AIC).

The Earth's total anthropogenic radiation balance is estimated at -2.29 W/m^2 of which aviation's contribution is estimated at approximately 3.9% (-0.09 W/m^2) of the total [1].

A surprising fast is that within aviation's contribution, *55% (0.050 W/m^2) is derived from Aircraft Induced Clouds*, and only 39% (0.035 W m^2) from CO_2, and 6% (0.05 W/m^2) from NO_x [2]. This is contrary to the popular belief that CO_2 is the main source of global warming from aviation activities.

Whereas the effect of CO_2 and other greenhouse gases on the lower atmosphere temperature structure takes approximately 20 years from the date it is emitted, the effect of AIC is *immediate*. In this way mitigating the effects of AIC on global warming can slow global warming and buy-time for longer term CO_2 initiatives to take effect.

Since AIC has greater impact than CO_2 (i.e. 55% vs 39%) and the effect of AIC is immediate, policy makers and industry have asked: What is the potential for mitigating AIC through technology advancement or operational changes?

The results of the analysis identify two groups of mitigation strategies that are segregated by the need for the airline fleet renewal.

The option with the highest utility and lowest cost is to make operational changes in the trajectory of the aircraft to fly over the super-saturated atmosphere. On average only 15% of the flights would be affected and the additional cost in fuel burn is negligible [3]. Other low-cost, near-term mitigations include adaptation of jet engine fuels. However significant investment in production capacity is required to produce bio and synthetic fuels in sufficient quantities even for blended fuel options.

Other options such as alternate energy sources (e.g. LNG, Hydrogen), or low-soot engines, require fleet renewal for implementation. These options should definitely be pursued as part of a long-term portfolio of mitigation strategies.

This paper is organized as follows: Section 2 provides an overview of the three types of Aircraft Induced Clouds. Section 3 describes the three processes in the formation of AIC and radiative forcing. Section 4 describes technologic and operational alternatives for mitigating AIC. Section 5 describes the results of a trade-off analysis of the alternatives. Section 6 concludes with the implications of these results and limitations of the study.

Overview Aircraft Induced Clouds

There are three types of AIC: (1) short-lived contrails, (2) long-lived persistent contrails, and (3) long-lived contrail cirrus.

Short-lived Contrails:

- Ice cloud type: Contrail
- Shape: Linear
- Atmospheric Conditions: Ice Sub-saturation
- Duration: < 10 minutes
- Dimensions (Depth x Width x Length): 100m x 10-100 m x 01.010 km
- RF Potential: Negligible

Long-lived Persistent Contrails:

- Ice cloud type: Persistent Contrail
- Shape: Linear
- Atmospheric Conditions: Ice Super-saturation
- Duration: 10 minutes – 10 hours
- Dimensions (Depth x Width x Length): 100m – 1000m, 100m-1000 m, 100m-10,000 m.
- RF Potential: 0.01 Wm^2 (20%)

Long-lived Contrail-Cirrus:

- Ice cloud type: Contrail-Cirrus
- Shape: Irregular shaped
- Atmospheric Conditions: Ice Super-saturation
- Duration: 10 minutes – 10 hours
- Dimensions (Depth x Width x Length): 100m – 1000m, < 100km, < 100km
- RF Potential: 0.04 Wm^2 (80%)

Short-lived contrails are present for less than 10 minutes, due the absence of atmospheric conditions to sustain ice-crystal growth (i.e. ice sub-saturated atmospheric conditions). They are distinctly line-shaped. The radiative forcing associated with short-lived contrails is negligible.

Long-lived contrails can be present from 10 minutes to 10 hours only when the atmospheric conditions are present to sustain ice crystal growth (i.e. ice super-saturation conditions). Persistent contrails remain line-shaped and can be as long as 10 km. They last from 10 minutes for up to 10 hours. Due to non-uniform winds, turbulent (random) motions and humidity fluctuations, the line-shaped clouds can lose their initial linear shape and morph into irregular shapes that resemble cirrus clouds. Over time, persistent contrails transition into contrail cirrus. The RF properties of long-lived contrails are a function of the 3-D volume of the clouds and the optical properties of ice crystals in the AIC.

The three AICs are shown in Figure 1.

Figure 1. Aircraft Induced Clouds (AIC): short-lived contrail (a), long-lived persistent contrails (b), long-lived contrail-cirrus(c)

The Three Processes in the Formation of Aircraft Induced Clouds

Aircraft Induced Clouds are generated as a result of a complex sequence of thermodynamic, fluid dynamic, chemical process (Figure 2). The generation of AIC can be described by three stages:

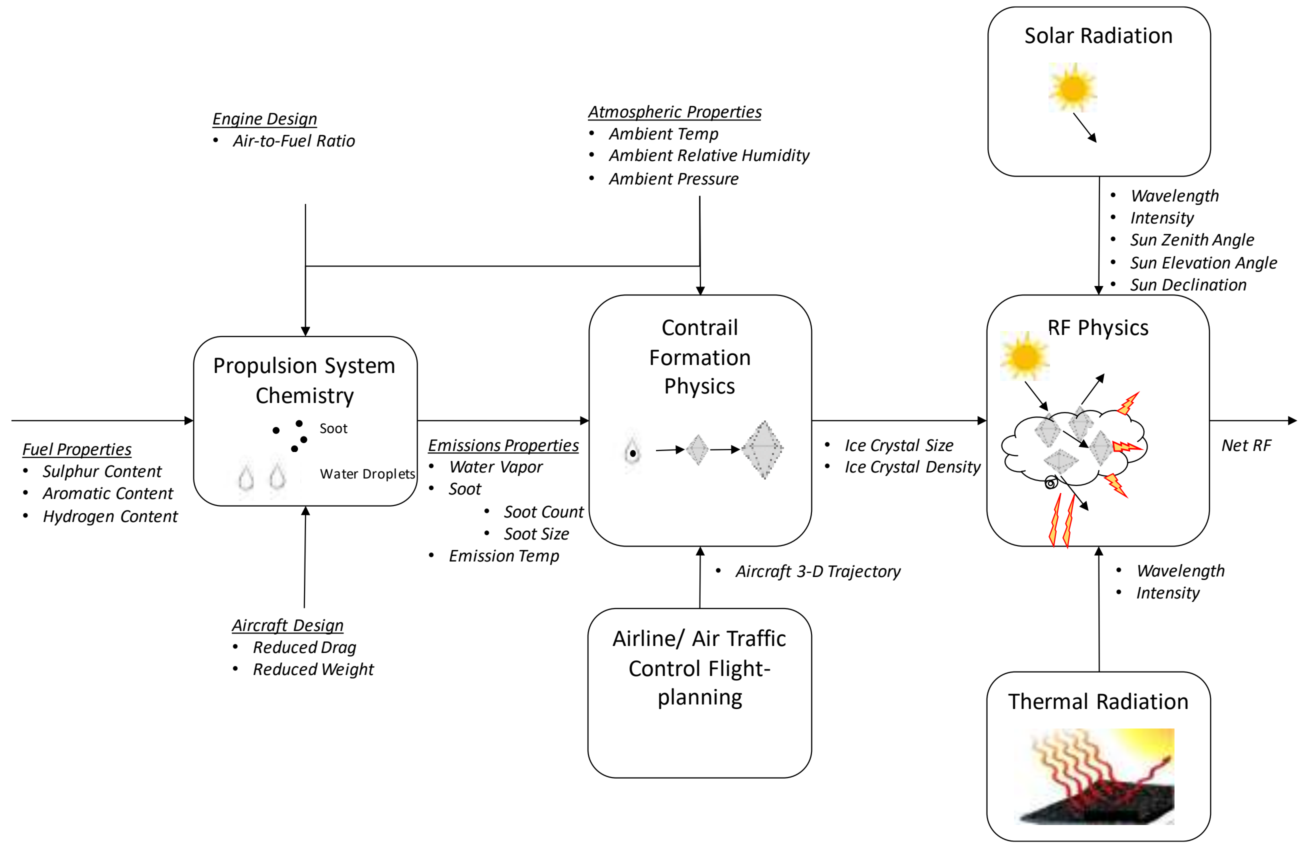


FIGURE 2: Summary of properties that affect contrail formation and spreading and the Radiative Forcing of clouds

(1) Jet engine emissions are mixed with the cold, humid ambient air and form ice crystals.

(2) Under ice super-saturated conditions, the ice crystals can grow and spread creating contrail-cirrus clouds.

(3) Radiative Forcing occurs when the ice-crystals absorb, scatter and transmit incoming short-wave "solar" radiation, and outgoing long-wave "thermal" radiation.

Propulsion Chemistry

Combustion of oxygen and hydrocarbon-based fuel results in the ejection of hot gases from the rear of the jet engine. Combustion is a chemical reaction between kerosene and oxygen that yields heat, light, CO_2 and H_2O. Approximately 1.24 tons of water is generated for each ton of kerosene.

Ice Crystal Formation

Natural cirrus and AIC (i.e. persistent contrails and contrail cirrus) are high altitude clouds composed of ice crystals that form and spread in Ice Super Saturated (ISS) regions [4].

ISS regions have cold and moist atmospheric conditions relative to ice phase saturation. These regions occur when the movement of continental weather patterns, such as maritime tropical air masses, transport moist air into colder regions

When a jet aircraft transits airspace that is not an ISS region, short-lived contrails may form in the drier or warmer (ice sub-saturated) air. These contrails are short duration (< 10 minutes), narrow, and do not absorb or reflect RF.

When a jet aircraft transits airspace that does meet the criteria for an ISS region, long-lived persistent contrails and contrail cirrus form. AIC and natural cirrus clouds are very similar except that AIC has a significantly higher number of ice crystals which results in reflection and absorption of incoming shortwave and outgoing longwave radiation.

There are two main stages of AIC evolution: (1) the Formation Stage, and (2) the Spreading Stage. In the Formation Stage, the initial short-lived contrails form directly behind the jet engines and last for about 10 min [5]. During the Spreading Stage, which follows the Formation Stage, the long-lived and cirrus contrails form (Table 2).

The formation of AIC is a complex set of thermodynamic, fluid dynamic and microphysical chemical processes that is beyond the scope of this paper. See [6], [7] for a more detailed description.

Formation Stage

Contrails begin to form in the jet regime when jet engine exhaust plumes expand, and their constituents mix with surrounding ambient air. When temperatures are below 233° K (≈−40 °C), short-lived and long-lived contrails can be seen behind the aircraft.

Soot particles, which figure most conspicuously in droplet formation, are caused by locally rich fuel-air mixtures within the jet engine combustor primary zone and, to a lesser extent, by high combustor operating pressures. The turbine breaks up some large soot particles while some small particles agglomerate in the exhaust plume to form larger particles. The highest level of soot typically occurs during takeoff and climb out when fuel flows and internal engine pressures are at their peak.

Significant ice nucleation (i.e. ice crystal formation) occurs only after water droplets have formed. The rates at which droplest freeze is inversely proportional to the rate of temperature decrease [8]. In this way, the number of ice crystals formed increases at a faster rate than the drop in the temperature.

The continued evolution of ice crystals depends on the interaction between the jet plumes and the wake vortex. The vortex, in which most of the contrail is captured will descend up to 100 m below the aircraft trajectory altitude. There is a partial loss of ice crystals due to sublimation in the lower part of the wake. The ice crystals present in the upper wake continue to grow by uptake of entrained ice super-saturated water vapor And grow to average ice crystal diameter of 1000 nanometers.

After the contrail has aged a few minutes, the ice crystal size distribution increases with signatures of nucleation, growth and sublimation. Eventually, flow instability triggered by turbulence causes the organized flow pattern to collapse and mix with ambient air thus terminating the formation stage.

Spreading Stage

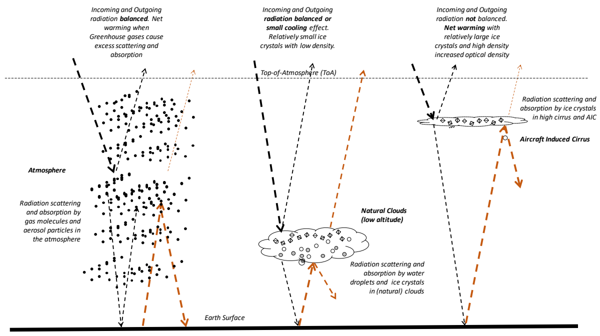
During the Spreading Stage, turbulent mixing (entrainment) forces cause ice crystal concentrations to decrease (dilute) over time. The ice crystal size, however, increases due to the uptake (deposition) of water vapor from ice super-saturated layers.

This sustained deposition growth causes ice crystal shapes (habits) to deviate from initial spherical isometry to , form droxtals, hexagonal prisms and columns, bullet rosettes and aggregates. These shapes determine size-dependent growth and fall rates, and optical properties. Ice crystals with maximum dimensions >30 µm settle (sediment) due to gravity with fall speeds > 100 meters per hour and sublimate in warmer or drier air. Smaller crystals remain around the flight levels due to negligible fall speeds as long as some supersaturation can be maintained.

The efficiency of sedimentation depends on the ice supersaturation, the rate of cooling of air, and on the size, habit and concentration of the ice crystals. Sedimentation increases the vertical extent of the AIC, which, in turn, enhances the rate of spreading and therefore coverage in the presence of wind. Sustained warming and drying due to large-scale subsidence (i.e. gradual sinking) dissolves the AIC entirely.

Radiative Forcing Physics

The Earth's radiation balance is measured at the Top of the Atmosphere (ToA) based on annual averages. The incoming shortwave (SW) radiation from the Sun is absorbed by the Earth and the atmosphere during daylight hours. The Earth subsequently emits outgoing longwave (LW) thermal radiation during the day and the night. When the climate is in balance, the incoming SW radiation is equal to the outgoing LW radiation [9].



(a) (b) (c)

FIGURE 3: Effect on Global Warming of atmosphere (left), natural (low) clouds with water droplets (middle), and high-altitude ice crystal AIC (right)

Naturally occurring clouds perturb this climate balance [10] (see Figure 3).

Anthropogenic impacts to the atmosphere such as the Greenhouse Effect from Greenhouse gases (e.g. CO2, methane) and from AIC also affect the climate balance.

The climate balance/imbalance is measured by Radiative Forcing (RF). RF is a first-order indicator of the radiation balance and is widely used to quantify climate change. RF refers to initial imbalances over a specified region and period of time. For example, the Intergovernmental Panel on Climate Change (IPCC) uses global averages taken relative to a pre-industrial time (1750). Global RF cannot be observed directly so it is estimated using models and by extrapolation of regional values inferred from satellite observations.

The effect of the Radiative Forcing (RF) at the Top-of-Atmosphere (TOA) produced by AIC is composed of the sum of the incoming solar shortwave radiation (RF_{SW}) and outgoing longwave radiation (RF_{LW}) and can be modeled as follows [11]:

$$RF = RF_{LW} + RF_{SW}$$

For long-wave radiation, the key parameters are:

- Optical Depth (τ)
- magnitude of the outgoing long-wave radiation (OLR)
- temperature (T)
- (soot) particle radius (reff)

For the short-wave radiation, the key parameters are:

- magnitude of the incoming solar radiation
- the Sun Zenith Angle

The RF from AIC (and all clouds) is determined in large part by the Optical Depth (τ) of the cloud. Cloud optical depths depend directly on the cloud thickness, the liquid or ice water content, and the size distribution of the water droplets or ice crystals. Optical Depth for clouds ranges from low values of less than 0.1 for thin cirrus to over 1000 for a large cumulonimbus.

The RF for clouds is directly determined by the cloud Optical Depth which is a function of ice crystal size and ice crystal density. In a cloud-less atmosphere (Figure 3-a), the radiation balance is maintained. Atmospheric gases and aerosol particles reflect, absorb, and transfer the same amount of incoming radiation as outgoing radiation. However, when greenhouses gases are introduced into the atmosphere, and a larger percentage of outgoing radiation is reflected back to Earth, the radiation balance is changed, resulting in a net warming.

Natural clouds are composed of water or a combination of water and ice crystals (Figure 3-b). Clouds dominated by water droplets form at lower altitudes. They have a net cooling effect by reflecting back into space a higher percentage of incoming radiation.

High altitude clouds are dominated by ice crystals (Figure 3-c). These high ice clouds are optically thin and partially transparent to solar radiation ($\lambda \approx 0.2$–$4\ \mu m$). As a result, they reduce the outgoing radiation (radiant energy with $\lambda > 4\ \mu m$) released into space via absorption and re-emission of LW radiation at cold temperatures. Also, their ability to scatter SW radiation back to space (known as albedo forcing) is low. The greenhouse forcing effect is stronger for higher and colder clouds with increased density of ice crystals.

Alternatives for Mitigating Aircraft Induced Clouds

Each of the three stages of AIC formation (Figure 2) provides an opportunity for mitigating Aircraft Induced Clouds (Table 1)

Propulsion System Chemistry

Jet engine emission properties generate soot. Approaches to reduce or eliminate soot count include aircraft design, jet fuel properties and engine design.

Aircraft Design

Soot count can be reduced by burning less fuel and due to reduced aerodynamic drag and reduced aircraft structural weight. One example is the blended wing body that has several efficiency advantages resulting in lower fuel burn and lower emissions [12].

Engine Design

Soot can also be reduced by engine design. Two approaches to reduce soot: (1) optimizing the operating condition and configuration of the combustor to produce less sooty flames, (2) dilution jets can be injected at a downstream location to dilute the mixture and provide oxygen to oxidize the soot [13]..

Rich Quench Lean (RQL) combustion minimizes the formation of nitrogen oxides in current combustion chambers [14]. The fuel is first burned with a fraction of the total air to ensure that the least amount of nitrogen oxides form. The remaining air is then introduced quickly and then lean burned in another combustion zone. To ensure that no pollutants leave the combustion chamber, any soot that forms in the first zone must be oxidized as much as possible in the second zone.

In-flight soot emissions can also be reduced by simply burning less fuel. Lean combustion technology that uses high air-to-fuel ratios during fuel combustion generates low soot particle emissions [15].

Jet Fuel Properties to Reduce Soot Counts

The major combustion products of conventional kerosene jet fuel are CO_2, water vapor, and soot. Soot count in the jet engine emission is the most critical parameter with regards to ice crystal formation and the resulting RF impact. There are two categories of fuel property modification: (1) drop-in fuels, (2) alternate fuels

<u>Drop-in Fuels</u>

The Sulphur and aromatic content of the jet fuel determine the soot count. Kerosene jet fuels can be produced with reduced Sulphur levels. Although the reduced-Sulphur kerosene has no impact on engine performance, there is evidence of increased in CO_2emissions (+0.1%) [16].

Synthetic fuels and biofuels can be produced to meet industry regulatory technical and safety standards providing for “drop-in” fuels that replace kerosene-based fuel without any changes to the fuel distribution infrastructure or engines [17]. These fuels contain low levels of Sulphur and aromatic species. Synthetic fuels are produced through the Fischer–Tropsch chemical processes from coal, natural gas or biomass. Biofuels are generated from feedstock, algae or biomass.

Pure biofuels significantly reduce soot count, however, they are unlikely to bring about a large reduction in AICs in the near term due to limitations in production capacity. As a consequence, kerosene-biofuel blends are typically used. The kerosene-biofuel blend has been shown to reduce soot particle emissions by 50% [18]. The impact on ice crystal numbers however is only −35% [19]. The lower nucleated ice numbers, due to reduced soot particle emissions, are compensated by enhanced sublimation losses.

Kerosene-biofuel blends tend to exhibit a higher hydrogen content relative to conventional jet fuel (+8%) [18] which slightly increases contrail formation threshold temperatures [20] (0.5–1 K). This increases AIC formation but does not lead to a significant increase in ice crystal numbers at the end of the formation stage (<5%) [21].

Pure synthetic fuels are still in the demonstration stage. The use of kerosene-synthetic fuel blends is expected to yield similar results as the blended kerosene-biofuels.

Blended fuels are widely used. The soot count is proportional to the percentage of the bio/synthetic fuel in the blend.

<u>Alternate Fuel Sources</u>

Although contemporary commercial jet engines are designed to operate exclusively with aviation kerosene, gas turbine engines can operate with a wide variety of liquid and gaseous fuels. Derivatives of aircraft jet engines are available for marine and industrial applications using natural gas, diesel fuel, alcohol, and other fuels. Future aircraft engines could also be configured to operate with alternative fuels, such as Liquid Natural Gas (LNG) or Liquid Hydrogen (LH2) [22].

Liquid hydrogen (LH2) and liquefied natural gas (LNG, consisting of mostly methane) have zero soot and Sulphur emissions. However, both fuels, especially LH2, generate increased water vapor. Super-cooled LNG is condensed from simple methane gas and sells for a fraction of the price. In a climate model study, RF due to a hypothetical fleet of LH2-propelled aircraft (cryoplanes) with increased water vapor emissions was smaller than that for kerosene aircraft [23].

Due to the limited space on an aircraft, natural gas or hydrogen would have to be stored in liquefied form. Although the energy density of hydrogen by weight is nearly three times that of conventional aviation fuels, the energy density by volume is one-fourth that of conventional aviation fuels. In addition, the potential weight savings of hydrogen fuel is offset by the additional weight of the liquid cryogenic fuel storage and handling systems and associated aircraft structures. The engineering challenges associated with accommodating low-density, cryogenic fuels in aircraft fuel tankage and supply systems are so substantial that their use can probably only be considered in new aircraft specifically designed for such fuels.

Other major impediments, especially with respect to hydrogen, include cost, availability, and infrastructure for production, transportation, storage, and aircraft servicing. Natural gas is readily available, but hydrogen must be produced. Hydrogen can be produced by releasing and collecting hydrogen from hydrocarbon fuels. This process releases 2 to 4 times more CO_2 than simply using hydrocarbon fuels directly as a jet fuel.

Electrolysis of water can also be used to generate hydrogen. This would require significant electricity not produced by fossil fuels. Burning hydrocarbon fuels to produce electricity to produce hydrogen to replace the use of hydrocarbons as a jet fuel would release more CO_2 than continuing to use conventional hydrocarbon jet fuel.

Full electrification of future generations of aircraft would lead to zero emissions of CO_2, NO_x and particles. The transition to electric flight, including long-range routes (e.g. transcontinental) is predicated by batteries sufficiently high energy density and motors with low weights. Hybrid propulsion systems with jet engines that generate electricity to drive electric motors is another option. Realistically, electrification can only apply to small aircraft designed for short-haul service.

Given the magnitude of these challenges and the long time frame it would take to develop and deploy significant numbers of new commercial aircraft equipped to operate with alternative fuels, it seems highly likely that commercial aviation will be dominated by aircraft powered by conventional jet fuels for the foreseeable future.

Trading Time versus Fuel-burn

Fuel-burn can also be reduced by optimizing operations. Airlines must trade-off time-enroute with fuel-burn. This is captured in the Cost Index, a ratio of time-costs/fuel costs, that airlines determine for each flight based on the desired aircraft utilization and other operational network considerations. A low cost index minimizes fuel-burn, but increases time-enroute.

Reduced Flight Demand

Another option to reduce fuel-burn is a reduction on demand for travel resulting in a reduction of the number of flights. There are several scenarios that could result in this outcome including increased fuel prices, and market-based schemes such as congestion pricing, slot auctions, and cap-and-trade.

Contrail Formation Physics

Once soot and water vapor have been emitted, very specific atmospheric conditions are required to generate AIC (Figure 2). A feasible mitigation strategy is to develop four-dimensional flight plans for airline, military, and government flights to avoid the ISS regions in the airspace. A case study of one year of flight operations in the contiguous United States (CONUS) identified that an average of only 15% of the flights each day (maximum 34%)

generate contrails [3]. Further, the contrail generation is mostly limited to geographic regions of the in south-east/mid-west and on the Pacific coast. A more general study of the atmosphere found that the fraction of the ice supersaturated altitudes in which aircraft actually fly (i.e. below FL430) is relatively small (10–15%) [24].

There are two ways to avoid the airspace with ISS regions: (1) fly around the perimeter, or (2) fly over/under. The horizontal width of ISS regions (>100 nm) makes routing around the ISS region prohibitive. Studies have found that lateral re-routing generated additional fuel burn costs that exceeded the environmental benefit [25], [26], [27].

Flying over the ISS region is a feasible option. A study of aircraft performance found that efficiency penalties are less than 1% when within roughly ±2000 ft. of the optimum cruise altitude [28]. A study of one year of flights in the U.S. found that when flights with planned routes through airspace with ISS regions had their Cruise Flight Level increased by 2000’ or 4000’ (if needed) it resulted in an estimated average daily decrease of -63% in NRF with a 2000’ increment in Cruise Flight Level, and an average daily decrease of -92% in NRF with up to a 4000’ increment in Cruise Flight Level [3]. These changes were considered statistically significant when compared to the original Cruise Flight Level at the 99% confidence interval. The difference in Fuel Burn between trajectories with the Original Cruise Flight Level and Fuel Burn with the incremental Cruise Flight Levels were not statistically significant. Additional fuel burn for climb and descent was counter-balanced by the lower drag at higher altitudes for long duration cruise segments.

This approach to avoid contrails is not new. Military operations frequently fly below or above ISS regions to avoid “conning altitudes” that result in the generation of contrails that provide a visual indication of the location of the (stealth) aircraft to adversaries.

Another alternative is to suppress ice crystal formation. Fuel additives could potentially coat soot particles with a highly “hydrophobic” material that makes them much less able to act as condensation nuclei for water vapor. Research is required to understand the chemistry and physics of the ice crystal coating. There are also questions on the impact of the additives on engine performance, the corrosive effects of the additives, and environmental implications of the additives [29].

RF Physics

Once soot and water vapor have been emitted, and the ISS atmospheric conditions are met, the next option is to leverage the properties of radiation. A theoretical, but impractical operational option, is to leverage the effect of the Sun Zenith angle on incoming short-wave RF. The concept would be to shift peak traffic towards sunrise and sunset to increase the albedo effect of the AIC reflecting a higher percentage of incoming radiation back out to space [28].

Fuel additives may also alter contrail optical properties. However, additional research required to understand the ice crystal formation and the impact of the additives. Questions on the impact of the additives on engine performance, the corrosive effects of the additives, and environmental implications of the additives must be addressed [29].

Other concepts include flight planning over existing clouds to avoid trapping additional thermal radiation. Also using precision navigation to lay contrails on top of each other. The impact on ice crystal formation, density and RF impact need to be studied

Trade-off Analysis of AIC Mitigation Alternatives

A multi-attribute utility analysis was conducted. Experts in each of the alternatives conducted an asynchronous Delphi process in determining attribute weights and attribute values.

The AIC mitigation options were assessed based on: Technology Readiness Level (TRL), Effectiveness in reducing AIC, and Deployment Time Frame. Each option was also assessed for Technology Development Costs and Technology Deployment Costs. The attribute weights and values are shown in the Tables in the Appendix.

Utility versus Relative Cost for each alternate is shown in Figure 4. The bars represent uncertainty of the estimates.

The options can be grouped into two clusters: near-term/low cost and long-term/significant costs.

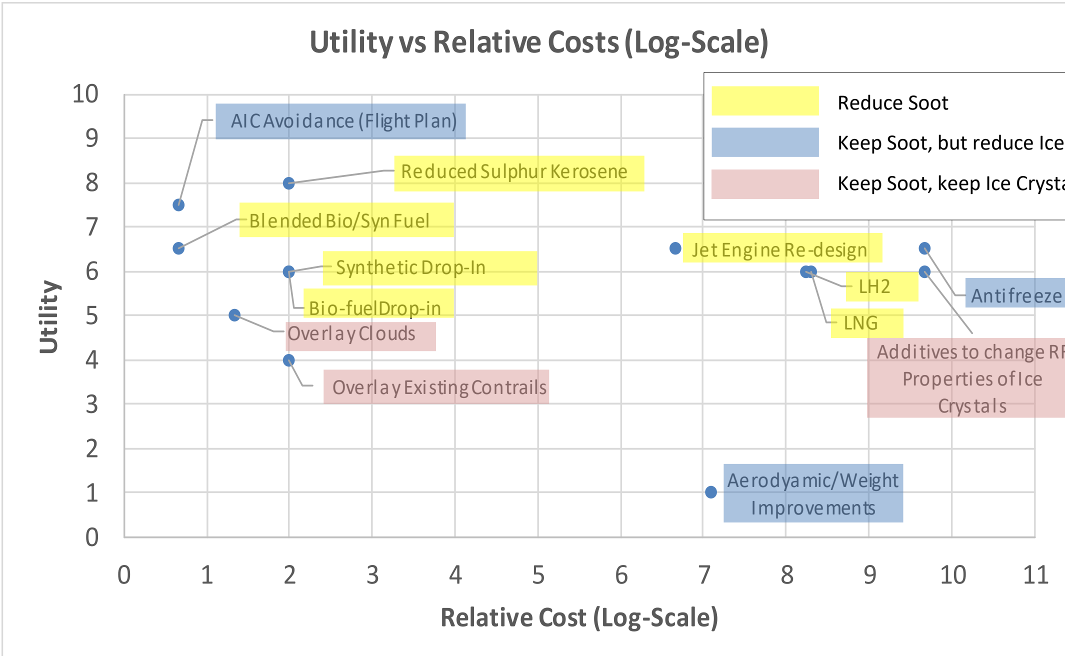


FIGURE 4: Utility vs Log-scale Relative Development plus Deployment Costs for each option

The most feasible near-term, low cost mitigation option is to manipulate Cruise Flight levels to minimize time in airspace with atmospheric conditions conducive to AIC generation. Operational changes for avoiding ISS regions can be implemented almost immediately, requiring some coordination between airline dispatch and air traffic management. The cost of implementation of the concept is low and the operational cost to the airlines (of additional fuel burn) is considered very low with benefits in good-will from customers.

The next near-term solutions, associated with reduced soot counts, are relatively low cost. Reducing soot emissions can occur through drop-in fuels (sulphur-free kerosene, biofuels, and synthetic fuels). Although technologically feasible, these solutions require significant increases in production capacity. Short-term solutions using blended kerosene fuels, reduce soot count by 50%.

Longer-term solutions that require significant investment in R&D, design and certification costs, and deployments costs: improved aerodynamics, engine design to reduce soot emissions, LNG and/or LH2 engines, and fuel additives to suppress ice crystal formation, or modify ice crystal properties.

Improved aerodynamics and reduced aircraft structural weights are beneficial but with a low utility. Reduced soot can also be achieved through engine re-design but there exists uncertainty in the technical feasibility and potentially high implementation costs. Alternate propulsion, such as LNG and LH2, require technology development as well as modification and/or creation of the fuel distribution infrastructure. Along with engine redesign, alternate propulsion and aircraft re-design for low drag there is a long transition period to replace the existing fleet.

Also, in the category of long-term initiatives is ice-crystal suppression and/or ice-crystal property modification through fuel additives. Several approaches to suppress the formation of contrails from the exhaust of a jet engine have been developed. One early approach was the injection of chlorosulfonic acid into the exhaust of an engine to diminish the particle size of water below the visible range. Chlorosulfonic Acid is a corrosive, clear liquid; melting point -80 C; boiling point 151 C; soluble in chlorinated solvents. It is hygroscopic and lachrymatory strongly. It reacts with water to form HCl. It is highly corrosive.

Significant research is required for the basic science of particle coating, as well as impacts on engine component corrosion, and environmental impact.

Conclusions

This paper provides and overview of Aircraft Induced Clouds (AIC), the "physics" of AIC formation and spreading, cloud properties with respect to Radiative Forcing, and identifying candidate interventions. The critical physical, chemical, and thermodynamic process are identified and used to intervene in the spreading of AIC including: the number of soot particles emitted by jet engines, the hydrogen content of emissions, jet engine emissions temperature, and location of atmospheric regions conducive to AIC spreading. A ranking of candidate technological and operational interventions is provided.

There are two groups of mitigation strategies segregated by the need for the airline fleet renewal.

The option with the highest utility and lowest cost is to make operational changes in the trajectory of the aircraft [3]. Other low-cost, near-term mitigations include adaptation of jet engine fuels. Significant investment in production capacity is required to make bio and synthetic fuels available in sufficient quantities even for blended fuel options.

Other options such as alternate energy sources (e.g. LNG, Hydrogen), or low-soot engines, require fleet renewal for implementation. These options should definitely be pursued as part of a long-term portfolio of mitigation strategies.

Scientific Uncertainty Associated with AIC

Whereas the aviation industry is committed to a sustainable future, there is justifiable reluctance to invest in technological and operational changes in which the benefits are uncertain.

There scientific understanding of the chemistry of jet fuel combustion and particle generation, and the physics of ice crystal formation from jet engine emissions is considered high.

The RF impact of AIC, the measurement and calibration of RF, and the impact of RF on the lower atmosphere temperature structure, however exhibits some uncertainty.

There are also complex interactions with secondary and tertiary climate effects that are not yet well understood.

With this in mind, the purpose of this paper is to assist in guiding the research and developing a set of hedging strategies for all plausible outcomes for contrail mitigation as the science improves and consensus is reached.

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Appendix

Mitigation Option								Utility vs Cost	
			Utility		Relative Cost				
Stage of Process	**Property Mitigated**	**Mitigation Technology**	**Technology Effectiveness**	**Deployment Time Frame**	**Technology Readiness**	**Technology Design Costs**	**Deployment Costs**	**Utility**	**Relative Cost**
Attribute Weights			**0.5**	**0.5**	**0.33**	**0.33**	**0.33**		
Propulsion System Chemistry	Less Soot	Lower Drag aerodynamics to reduce Fuel Burn	Low (reduces fuel burn only)	Long (fleet replacement)	High	High (redesign and certify new airframe)	High (fleet replacement)	**1**	**7.1**
		Jet Engine Re-design (air-to-fuel ratio, combustor redesign dilution jets)	High (has potential to significantly reduce soot)	Long (engine replacement or fleet replacement)	Medium	Medium (modify existing engines)	High (engine replacement or fleet replacement)	**6.5**	**6.7**
		Reduced Sulphur kerosene	High (reduces soot)	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Low (change to refining process)	**8**	**2.0**
		Biofuel Drop-In	Medium (used in kerosene blend, cannot scale production)	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Medium (significant increase in production capacity)	**6**	**2.0**
		Synthetic fuel Drop-In	Medium (used in kerosene blend, cannot scale production)	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Medium (significant increase in production capacity)	**6**	**2.0**
		Blended Bio/Synthetic fuel Drop-In	Low	Now (Drop-in fuel)	High	Low (Drop-in fuel)	Low	**6.5**	**0.7**
	No Soot	Liquid Natural Gas (LNG)	High	Long (fleet replacement, new infrastructure)	Medium	High (design and certify new engine)	Very high (needs new infrastructure)	**6**	**8.2**
		Liquid Hydrogen	High	Long (fleet replacement, new infrastructure)	Medium	High (design and certify new engine)	Very high (needs new infrastructure)	**6**	**8.3**

Mitigation Option								Utility vs Cost	
			Utility		Relative Cost				
Stage of Process	**Property Mitigated**	**Mitigation Technology**	**Technology Effectiveness**	**Deployment Time Frame**	**Technology Readiness**	**Technology Design Costs**	**Deployment Costs**	**Utility**	**Relative Cost**
Attribute Weights			**0.5**	**0.5**	**0.33**	**0.33**	**0.33**		
Contrail Formation Physics	No ice crystals	Flight plan based on atmospheric conditions to avoid ISS Regions	High (may not eliminate all AICs)	Now	High	Low	Low	**7.5**	**0.7**
		Fuel additives to suppress ice crystal formation	Medium	Immediate	Low	High	High	**6.5**	**9.7**
RF Physics	Reflection, Absorption properties of AIC	Flight plan Overlay on Existing Clouds	Medium	Immediate	High	Low	Low	**5**	**1.3**
		Flight plan Overlay on Existing Contrails	Low (reduces fuel burn only)	Immediate	High	Low	Low	**4**	**2.0**
		Reflection, Absorption properties ice crystals	Medium	Immediate	Medium	High	High	**6**	**9.7**