DESIGN OF AN AIRCRAFT INDUCED CLOUD (AIC) ABATEMENT PROGRAM (AAP) FOR GLOBAL WARMING MITIGATION

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Abstract

Aircraft Induced Clouds (AIC), also known as Contrails, absorb, scatter and reflect back to the Earth an estimated 33% of the outgoing "thermal" radiation emitted from the Earth that is directed at the cloud. The resulting global warming is estimated to account for 55% of aviation's total contribution to global warming. The CO2 emissions from aircraft is estimated to account for only 39% of aviation's total contribution. Recent studies of options to mitigate the global warming effects of AIC identified that the most cost effective and near-term solution is an "operational" change such that flights fly over the Ice Super Saturated Regions (ISSR) in the atmosphere in which AIC are generated. This operational change would affect, on average, only 15% of the flights each day and would add no net direct operating cost to the airlines or Air Traffic Control while reducing global warming immediately.

When the industry decides to take advantage of this global warming mitigation opportunity, an AIC Abatement Program (AAP) will need to put in place. This paper provides a System Design for a collaborative Airline and Air Traffic Control system to mitigate AIC by managing Cruise Flight Level assignment relative to the presence of ISSRs. The paper identifies the objectives of the system, protocol, incentives, rules to prevent "gaming the system," and a functional description of an evaluation tool to operate the proposed AAP. The implications and limitations of the proposed system, along with topics for future work are discussed.

INTRODUCTION

Global warming has long been accepted as a "price" of mobility. The cost of propulsion emissions is considered an "external cost" that is borne by nameless, unidentified "others."

According to the Intergovernmental Panel on Climate Change (IPCC) report, Earth's current total anthropogenic radiation balance is estimated at -2.29 W/m2 of which aviation's contribution is estimated at approximately 3.9% (-0.09 W/m^2) of the total [1], [2]. A surprising fact is that within aviation's contribution, 55% (0.050 W/m^2) is derived from Aircraft Induced Clouds (AIC), and only 39% (0.035 W/m^2) from CO2, and 6% (0.05 W/m^2) from NOx [2]. The contribution of CO2 at 35% is contrary to the popular belief that CO2 is the main source of global warming from aviation activities.

Aircraft Induced Clouds (AIC), also known as Contrails, absorb, scatter and reflect back to the Earth an estimated 33% of the outgoing "thermal" radiation emitted by the Earth that is directed at the AIC. This radiation, otherwise transmitted out to space, results in an increase in the Earth's temperature structure [1]. AIC also can provide a cooling effect, reflecting 23 % of the incoming "solar" radiation back out to space. The cooling effect only takes place in daylight hours. Note: on aggregate, during daylight, AIC has a net warming effect (33% - 23% = 10%).

It should be noted that the physics, chemistry, and science of global warming and the greenhouse effect is complex with primary and secondary effects (i.e. feedback loops and interactions). As a consequence, the estimated impact of AIC, CO2 and other factors on global warming is reported with an uncertainty band. In Lee et.al. [2], the uncertainty band for AIC is 5X the uncertainty band for CO2, and 2X the uncertainty band for NOX.

Whereas the effect of CO2 and other greenhouse gases on the lower atmosphere temperature structure takes approximately 20 to 40 years from the date it is emitted, the effect of AIC is immediate. For these reasons, it may behoove the industry to develop plans to mitigate the global warming effects of AIC.

Avila, Sherry & Thompson [3], using archived and simulated flight track data, along with the best available models of contrail formation and persistence, and models of contrail radiative forcing, identified the following facts:

- Contrails are generated by an average of only 15% of the daily flights (max 34%).
- The location of the contrails depends on atmospheric conditions, known as Ice Super Saturated Regions (ISSRs), and occur mostly in the south-eastern and mid-Atlantic region of the United States and on the Pacific Coast.
- The weather conditions conducive to contrail formation are more likely to occur in the Summer months.
- Contrail formation can be avoided by increasing the Cruse Flight Level by between 2000' and 4000' feet.
- Due to low air density at Cruise Flight Levels, the additional fuel burn required to climb to the higher cruising altitude is mitigated by reduced fuel burn due to reduced Drag at the higher altitude.
- In a small percentage of cases, under specific circumstances (e.g. Sun Azimuth), AIC can yield a net cooling effect.

Similar results were reported by Teoh et.al [4] for Japanese airspace, and Rosenow et.al. [5] for European airspace.

These results indicate the feasibility of an AIC Abatement Program (AAP) to mitigate the effects of aviation's anthropogenic effects on global warming.

This paper describes the concept-of-operations for an AAP: the objectives of the program, a protocol, incentives for participation, and rules to prevent gaming. The paper also provides a functional description of a tool for flight plan AIC abatement evaluation.

The paper is organized as follows: Section 2 provides an overview of AICs. Section 3 describes a portfolio of AIC mitigation strategies and the rationale for the approach described in this paper. Section 4 provides an overview of the Flight Planning Process, Cruise Flight Level selection, and Air Traffic Flow Management. Section 5 describes

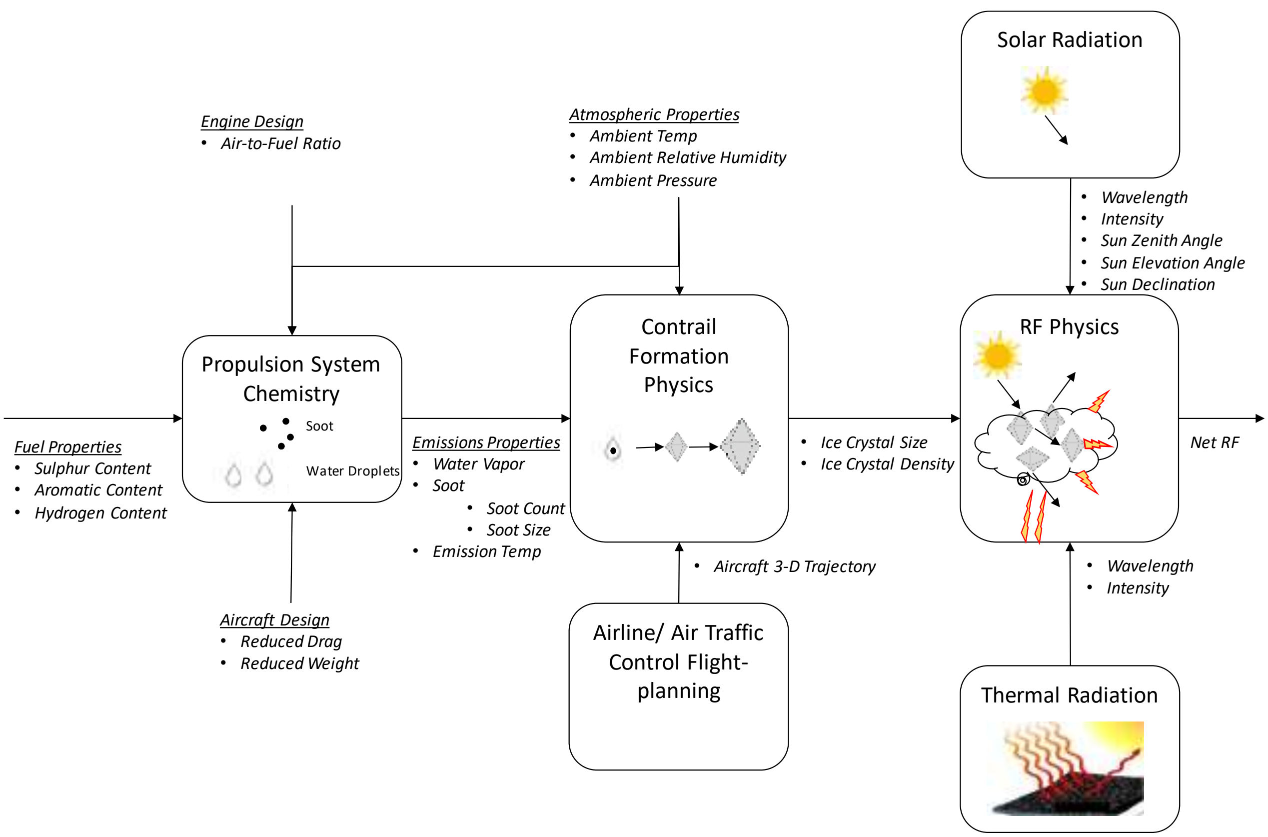

FIGURE 1: Summary of properties that affect contrail formation and spreading and the Radiative Forcing of clouds [6].

the design of a system for AIC mitigation: objectives, protocols, incentives, rules to prevent gaming, and the functional design of infrastructure. Section 6 discusses the implications and limitations of the proposed system, along with topics for future work.

OVERVIEW OF AIR CRAFT INDUCED CLOUDS (AIC) AND GLOBAL WARMING

The Net Radiative Forcing (NRF) from AIC is the result of the sequence of chemistry and physics summarized in Figure 1. In the contemporary aviation system, jet engines burn kerosene-based fuels that generate water vapor and soot particles. In a complex thermodynamic, fluid dynamic, chemical process, the jet engine emissions are mixed with the cold, humid ambient air and form ice crystals. Under ISS conditions the ice crystals can grow and spread creating contrail-cirrus clouds. These clouds impact RF by absorbing, scattering and transmitting incoming short-wave "solar" radiation, and outgoing long-wave "thermal" radiation.

There are three types of AIC: (1) short-lived contrails, (2) long-lived persistent contrails, and (3) long-lived contrail cirrus. AICs are categorized as short-lived with duration less than 10 minutes, and long-lived with durations up to 10 hours (Figure 2). Short-lived contrails are line-shaped and have short duration due to ice subsaturated atmospheric conditions that do not sustain contrails. Radiative forcing associated with short-lived contrails is negligible.

Long-lived contrails are split into two categories: Persistent and Cirrus. Persistent contrails remain line-shaped and can be as long as 10 km. They last from 10 minutes for up to 10 hours. Over time, due to non-uniform winds, turbulent (random) motions and humidity fluctuations, persistent contrails lose their initial linear shape and transition into contrail cirrus with irregular shapes. These contrails can overlap and merge with other contrails in traffic-congested areas, forming extended ice cloud layers with non-uniform shapes, depth and duration. The persistent contrails may also merge with or form in natural cirrus. AIC can also be transported considerable distances (e.g. 100 km) away from their location of generation, resulting in AIC presence in locations where ISS conditions are not met. 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.

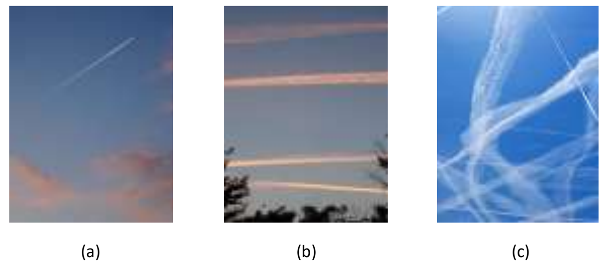

FIGURE 2 Aircraft Induced Clouds (AIC): short-lived contrail (a), long-lived persistent contrails (b), long-lived contrail-cirrus (c)

OPTIONS FOR MITIGATING AIC GLOBAL WARMING EFFECTS

There are a range of options for mitigating AIC described in [6] and summarized in Figure 3. 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 are associated with reduced soot counts are relatively low cost. Reducing soot emissions can occur through drop-in fuels (Sulphur-free kerosene, bio-fuels, 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 require significant investment in R&D, design and regulatory certification costs, and deployments costs. These

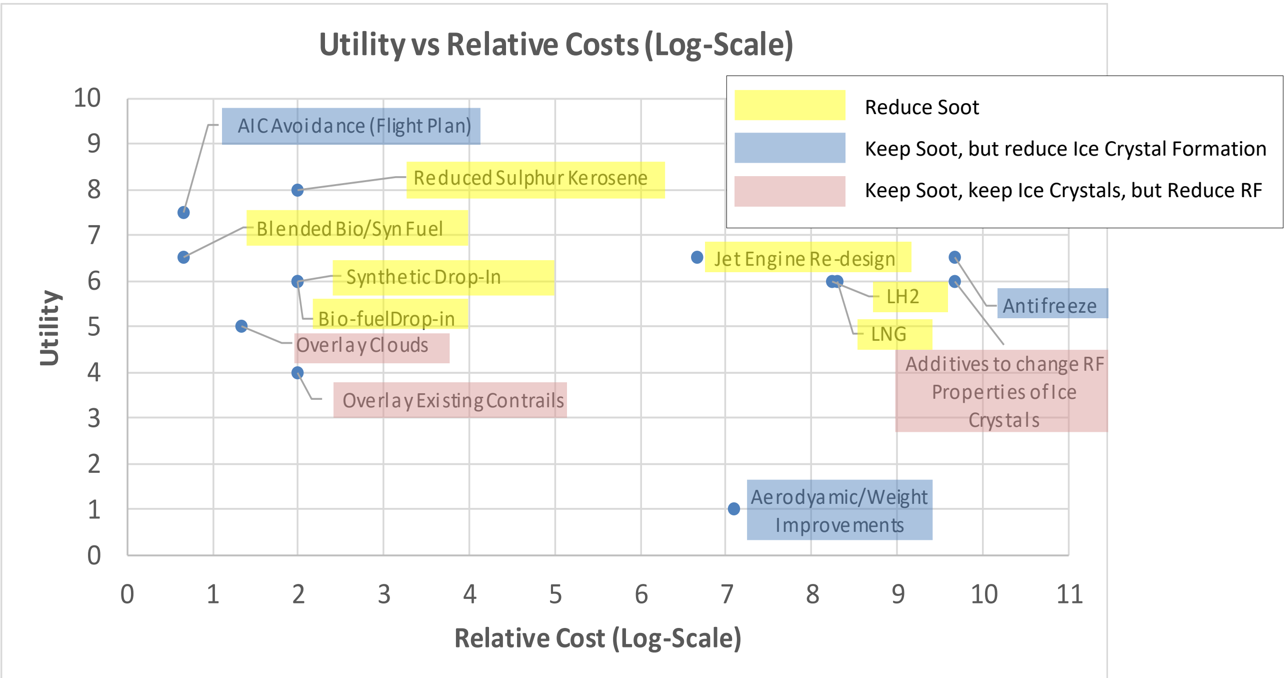

FIGURE 3: Utility vs Log-scale Relative Development plus Deployment Costs for AIC mitigation options [6]

include 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. Also, in the category of long-term initiatives is ice-crystal suppression and/or ice-crystal property modification through fuel additives.

Operational Changes to Avoid Flying in ISSR

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%) [7].

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 [8].

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 [9]. 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.

OVERVIEW OF FLIGHTPLANNING AND CRUISE FLIGHT LEVELS

An AIC Abatement Program (AAP) will need to adjust the Cruise Flight Levels that are part of the flight plan. This section provides an overview of the flight plans used for air traffic control and the role of the Cruise Flight Level. This section also provides an overview of Traffic Flow Management Initiatives (TFMI) and their ability to provide airlines with incentives for “cooperative” behaviors in a competitive marketplace. These incentives are option for the proposed AAP.

A Flight Plan

A flight plan defines the four-dimensional trajectory of a flight. The lateral plan is defined by latitude/longitude fixes or waypoints. In many cases the sequence of waypoints is defined by navigation procedures such as jet airways, departure procedure or standard arrival procedures. The vertical plan is defined by altitude constraints at waypoints and the Cruise Flight Level(s). The time plan is defined by a combination of speed limits, speed constraints at waypoints, and time constraints at waypoints.

The flight plan must account for the performance limits of the aircraft under the atmospheric and weather conditions in which the flight will be conducted.

Optimum Cruise Flight Levels

A key element of the flight plan is the Cruise Flight Level. The Cruise Flight Level for the flight is generally set to the Optimum Cruise Flight Level which takes into account payload, fuel burn rates, atmospheric conditions (e.g. outside air temperature), and weather (e.g. head/tail winds) [9]. The Optimum Cruise Flight Level also accounts for airline specific considerations that are based on airline policies and costs of operations. These factors are captured by a parameter known as the Cost Index (CI). The CI is set for each flight and is based on a trade-off of airline fuel costs and airline labor costs for the flight.

The Cruise Flight Level is also constrained by the Maximum Cruise Flight Level. This is determined for a given flight by payload and fuel weight, as well as atmospheric conditions. The Maximum Cruise Flight Level will increase as the flight progresses and fuel is burned. Max Crz FL does not exceed FL430.

Flight Planning Process

In addition to airline considerations, the flight plan must also account for air traffic control considerations including airport flight arrival demand vs, airport capacity, airspace density and congestion. In this way the flight plan is the result of coordination between Dispatchers, Air Traffic Control, and the Flight Crew. The flight planning process is as follows:

Dispatchers

Dispatchers are tasked with flight planning and dispatching the flight. This includes coordinating with the airline meteorology department for weather considerations, and with the airline Maintenance department for any inbound maintenance issues. The flight plan selected by the dispatcher is typically a standard route developed by the airline for efficiency. The dispatcher may choose to deviate from the standard route if weather or operational issues require such as thunderstorms, areas of turbulence and headwinds winds at altitude.

Air Traffic Control

Dispatchers file the flight plan with Air Traffic Control (ATC). ATC reviews the flight plan for forecast airport arrival demand in excess of airport capacity, airborne traffic congestion, weather storms, and turbulence. ATC can accept or amend the submitted route when the route a dispatcher files is different from the ATC’s preferred route, or there are weather, congestion, or demand/capacity imbalances. The change can be small, with just a couple new fixes, or large, requiring coordination with dispatch and additional fuel planning.

ATC will generally accommodate the dispatch requested Cruise Flight Level.

Prior to departure or during a flight ATC can modify a filed flight plan This is known as an ATC reroute. Once a flight is underway, ATC can change the flight's route by offering the pilots a more direct path to their destination, a change to avoid weather, or a new arrival time at their destination to better manage the flow of traffic. If ATC issues a large route change, the flight crew must coordinate with the flight's dispatcher to ensure there is adequate fuel to fly the new route.

Flight Crew

The flight crew have final authority for conduct of the flight. The flight crew will review the flight plan released by dispatch and approved by ATC to become familiar with the route. Any potential issues with the route (e.g. developing weather), are resolved by working with the dispatcher. Changes to the flight plan require the dispatcher to amend the release and to file a new route with ATC before the flight departs.

Once the flight is underway, the flight crew are continuously reviewing the flight plan. The flight crew may request shortcuts from ATC if they think that they can save time or fuel (i.e. Direct To) or modify the route if they need to avoid weather. If the weather is significant enough, the flight crew will ask ATC to deviate away from it, then coordinate with the airline dispatcher to find an alternate route. Since the longer an airplane flies, the more fuel it consumes, the route must be coordinated to ensure that adequate fuel is on board the aircraft.

Traffic Flow Management Initiatives & Incentives

Traffic Flow Management Initiatives (TFMI) are programs coordinated by Air Traffic Control to address situations when a resource, such as airport gates, runway slots, or airspace slots, are temporarily over-subscribed. In these situations, TFMI will institute programs such as Ground Stop (GS) for airport departing flights, Ground Delay Program (GDP) for airport arriving flights, Air Flow Program (AFP) and Miles-In-Trail (MIT) for airspace congestion. In each program, slots are allocated by ATC according to specific protocols designed to equitably and efficiently flow traffic. One example of a protocol is First-Scheduled-First-Served (FSFS).

For these programs to work, airlines must participate in the program by sharing information, with ATC such as canceled or delayed flights. To incentivize airlines to share this information, the airlines can earn prioritization credits known as "exemptions," "slot swapping" or "substitution." These credits prioritize the airlines flights in the allocated slot schedule.

This concept of allocating credits for TFMI is an important part of the AAP as discussed in the next section.

CONCEPT-OF-OPERATIONS: AIC ABATEMENT PROGRAM (AAP)

This section describes the design of a system for an AIC Abatement Program (AAP):

1 Objectives

2 Protocols

3 Incentives

4 Rules to Prevent Gaming

5 Functional Design of Flight Plan AIC Abatement Evaluation Tool

Objectives of AIC Abatement Program (AAP)

The objective of the AIC Abatement Program (AAP) is to manage the warming effect of NRF from AIC. This can be accomplished by the *one* of the following options for objectives listed by increasing complexity:

1. minimize the warming effect from AIC for each flight (i.e. no NRF target, just do best)
2. not to exceed an upper limit of total NRF from AIC from all flights (i.e. minimize the NRF across all flights not to exceed an airspace NRF inventory limit)
3. minimize the warming NRF from AIC and maximize the cooling NRF effect for each flight according to an objective function

The first proposed objective is the simplest. This objective assumes that each flight that generates an AIC has a net warming effect. This objective would attempt to raise the Crz FL for every flight forecast to traverse an ISSR (see protocol below) without accounting for the impact of the flight or any potential cooling effects.

The second proposed objective is to establish an upper limit on the daily or monthly inventory of NRF from flights. This approach would emphasize the flights that are highest NRF generators. This would affect a smaller percentage of flights, but would also not account for any potential cooling effects.

The third proposed objective is the most sophisticated. This objective would assess each flight's NRF and weigh the benefits of a Crz FL change with the NRF (warming or cooling).

AIC Mitigation Protocol

These objectives can be accomplished by the following protocol.

In addition to all the traditional considerations described above for flight planning, the Flight Planning process shall also take into consideration the presence of Ice Super Saturated Regions (ISSR) in the airspace. Using models of AIC formation and persistence, and models of radiative forcing, the flight plan can be evaluated to determine if it generates AIC, and if the AIC have a warming or cooling effect (e.g. favorable Sun azimuth).

Each flight plan is evaluated on its potential to generate an AIC with a warming effect based in the following criteria:

1. transit an ISSR for more than a minimum distance (e.g. 10 nm), and
2. the flight is estimated to form contrails that persists for more than a minimum time (e.g. 20 minutes), and
3. the predicted AIC is predicted to generate a warming effect in excess of a minimum threshold

In the event the three conditions above (i.e. ISSR present, AIC forms, and AIC is warming) apply to a given flight plan, the airline (i.e. dispatcher) can choose to maintain the preferred Cruise Flight Level and generate AIC with a warming effect. Alternatively, the dispatcher can amend the flight plan for a higher Cruise Flight Level (subject to Maximum Crz FL, turbulence, etc. considerations) that allows the flight to occur above the ISSR.

In the event the airline files a flight plan with a warming effect, ATC can request an amendment to the Cruise Flight Level subject to Maximum Crz FL, turbulence, etc. considerations. In this case, the airline can earn TFMI exemption/credits (see next section). The airline can decline the Crz FL amendment.

Incentivizing Amended Cruise Flight Levels for AIC Mitigation

According to aircraft performance models [8], [9], within a range of optimum cruise speeds, the optimum cruise flight level can be adjusted within 2000' and 4000' feet without any fuel penalties due to additional climb to the higher altitude or cruise at the higher altitude.

In the event a given flight is penalized by additional fuel burn by the amended Crz Flight Level, or the airline chooses not to accept the amended Crz FL, it may be necessary to incentivize the change in Crz FL to mitigate AIC.

There are three approaches to incentivizing airlines.

1 Traffic Flow Management Initiative Exemptions and Credits

A flight with a flight plan that traverses an ISSR would be given a TFMI Exemption or a TFMI Credit for slot Substitution/Swapping if the flight plan Crz FL is above the ISSR. The exemption/credit could be used by the airline on any of the airline's flights.

There probably would need to be an upper limit that could be used by one airline in a given TFMI to avoid under-cutting the TFMI. There would also need to be an upper limit used across all airlines in a given TFMI to avoid under-cutting the TFMI.

2 Hall of Fame/Hall of Shame Scorecard

Publish a quarterly scorecard for each airline. Airlines that voluntarily reduce their NRF contribution would garner consumer benefits. The value to an airline in increased revenue or sales is an open question.

3 Government Subsidized Bio-Fuel Prices/Extra Cost Reimbursement

Government would subsidize Sustainable Aviation Fuel (SAF) (or other potential low soot fuels) proportional to the forecast count of flights generating AIC, magnitude of total along-track distance of AIC, or total AIC NRF. This incentive would have a double benefit of generating demand and stimulating production for the fledgling aviation SAF industry.

Preventing "Gaming" to get TFMI Exemptions/Credits

With the introduction of the incentive scheme described above it is possible that an airline might choose to "game the system." That is not violate the rules for filing flight plans per se, but take advantage of natural loop-holes in the rules against the spirit of the initiative.

This would occur in the case when an ISSR is present and the optimum cruise flight level for a flight is above the ISSR (i.e. the flight will not generate a warming AIC). In this case, the airline could file a flight plan with a lower, AIC-warming-Crz FL expecting ATC to amend the Crz FL and award the airline a TFMI Exemption/Credit. If the Crz FL amendment was not given by ATC, the flight crew may request a new higher flight Crz FL change that would bring the flight to the Optimum Crz FL.

To avoid gaming AAP could:

1 Check the Crz FL. The planned Crz FL could be verified by comparing it to the Optimum Crz FL. This would require detailed information on the Takeoff Gross Weight, Cost Index and other flight and airline specific information to assess if the flight legitimately would operate at a Crz FL in the ISSR.

2 Limit the exemption/credit only to the Flight Affected. This would limit airline gaming of the system by using this trick only if the flight in question was subject to a probable TFMI. With this rule the airline would not be able to accumulate TFMI exemptions/credits to use on other flights. This rule might severely limit the value of the incentive. It might also result in the award of excess exemptions to a GDP at a given airport (e.g. LGA, EWR) that defeats the purpose of the GDP.

3 Monitor for Systemic Gaming Behaviors: Monitor airline flights over an extended period of time (e.g. month, quarter, year) to identify systemic behaviors of filing low Crz FLs on the same flights, or systemically filing low Crz FLs and then flying high. In the event the criteria for systemic gaming are identified, the airline could lose TFMI Exemptions/Credits and/or be fined. The fines would follow the same protocol for airline maintenance and Tarmac Delays.

Functional Design of Flight Plan AIC Evaluation Tool

Flight Plan AIC Evaluation Tool is designed to determine the presence and magnitude of AIC for a given flight plan for a specific day (i.e. atmospheric conditions. The input to the tool is the Flight Plan. The output of the tool is AIC 4-D location (if any), AIC Along-Track Distance, AIC Duration and AIC NRF. The ISSR location is determined from atmospheric data (e.g. NOAA RAP Data). The ISSR Location is combined with Flight Plan and AIC Formation and Persistence Models to generate the 4-D Location of the AIC. The 4-D Location of the AIC along with an AIC NRF Model is used to calculate the NRF.

Examples of models that demonstrate the features of this tool include: Avila [3], Teo & Stettler [4] and Rosenow [5]. Contrail Formation and Persistence Models are evolving rapidly (e.g. Karcher [10], as are Contrail NRF Models (e.g. Shuman [11]).

CONCLUSIONS

When the aviation industry decides to leverage the opportunity to mitigate AIC, an "Air Traffic Control Program" will need to be established. The proposed AIC Abatement Program will operate much like existing Traffic Flow Management (TFM) Programs (e.g. Ground Delay Program (GDP) and Air Flow Program (AFP)).

This paper provides the objectives of the proposed AAP, a protocol, incentives and rules to prevent gaming need to be established. This paper also provides a functional description of the Flight

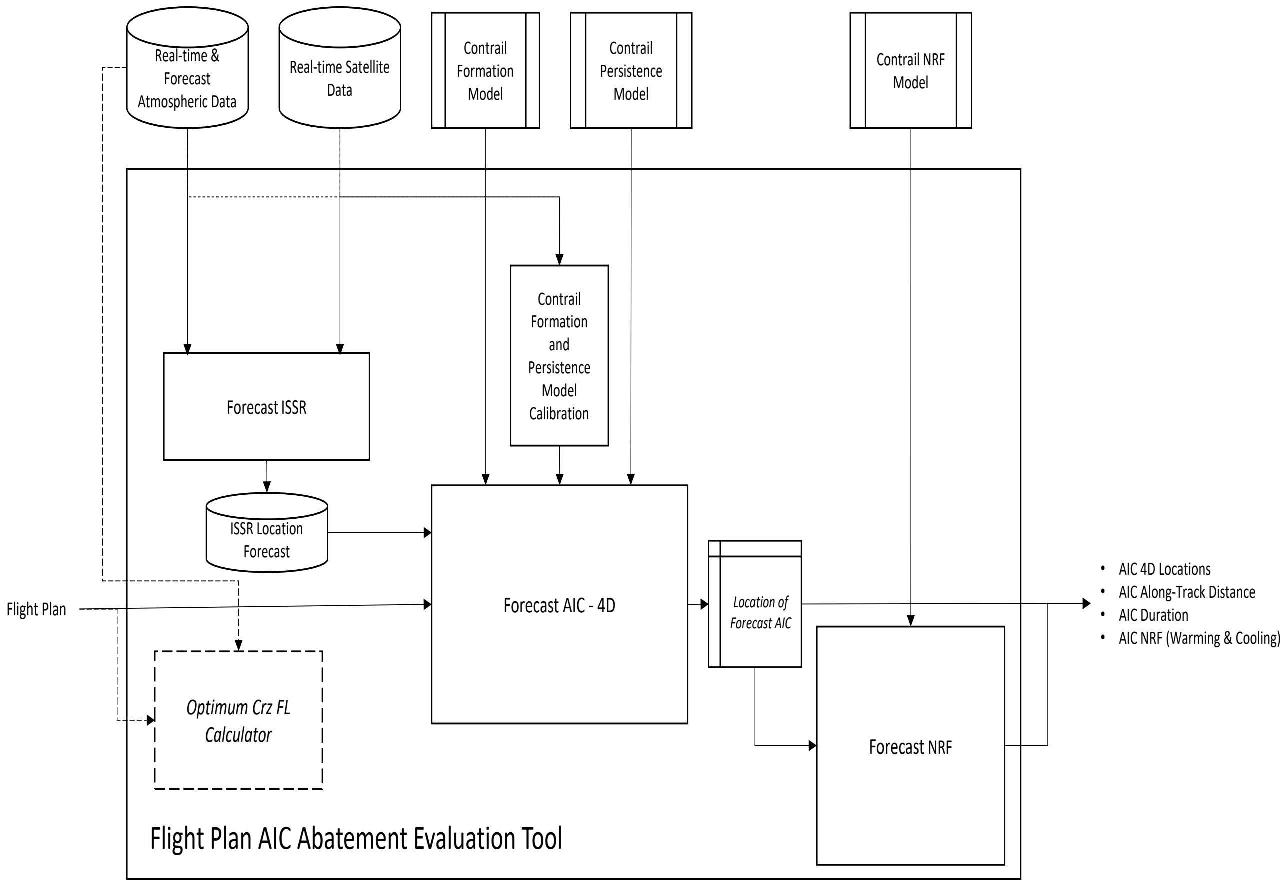

FIGURE 4: Function Description of Flight Plan AIC Evaluation Tool

Plan AIC Abatement Evaluation Tool (FPAAET) for managing Cruise Flight Level assignment relative to the presence of ISSRs.

The protocols and rules for the AAP require additional work to design the details. It is anticipated that a Human-in-the-Loop (HITL) war-game testing with multiple airlines and TFM will need to played to develop a complete set of rules.

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