Design of a Decision Support System to Reduce Net Radiative Forcing via Optimal Contrail Generation

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Abstract— **With global flight distance projected to increase by a factor of four by 2050, contrail generation is expected to increase by a similar factor. Optimized contrail presence can lead to decreased net radiative forcing (RF): the phenomenon that occurs when heat is trapped within the Earth's atmosphere. RF is projected to increase by 280% by 2050, adding significantly to global warming. A system needs to be developed to utilize the opportunity in aircraft contrail generation optimization; this will help to prevent radiation from entering the Earth's atmosphere and allow outgoing heat to escape. Controptimal is a decision support system (DSS) for airline dispatch that was created to help address this gap and reduce net radiative forcing. Specifically, a simulation was developed to optimize contrail generation to lower net radiative forcing. Of the nine altitudes analyzed, two proved to lower net RF by at least 20% with the most optimal route flying at FL 330 and decreasing the baseline RF value by 94%. However, RF values were found to decrease further when the system used live weather data. The simulation utilized a network optimization to then conduct a tradeoff between net radiative forcing, fuel burn, and duration of flight. In a specific case study timestamped '2015-08-16 09:00,' Controptimal found an optimal route that began at FL 330 and ascended to FL 380 one hour into the flight. By flying this route, it decreased net RF by 94%, increased fuel burn by 3%, and increased flight time by approximately 4 minutes. This trajectory had a utility of 0.65, followed by an alternative with a utility of 0.49. The results indicate that contrail presence could be planned to lower the net RF.**

Index Terms- Contrail, Radiative Forcing (RF), Ice Super Saturated Region (ISSR), Shortwave Radiative Forcing, Longwave Radiative Forcing, Albedo, Solar Zenith Angle

I. Introduction

THE commercial domestic airline transportation enterprise in the United States was responsible for carrying over 650 million passengers in 2015. The Federal Aviation Administration (FAA) predicts that the demand for air travel will increase by an average of 2.1 percent per year over the next 20 years, where a total of over one billion passengers will be serviced per year [1]. Accompanying this increase in air travel is increased aviation-based emissions. The burning of jet fuel produces several different emissions, most notably CO_2, water vapor, and soot – all of which relate to contrail generation.

Contrails, or condensation trails, are created in the wake of an airplane and estimated to be the largest factor in aviation-specific radiative forcing [2]. They are the result of hot water vapor and soot molecules mixing and condensing after being exposed to cold temperatures. Areas where there is a high probability of contrail generation are called Ice Super Saturated Regions (ISSRs).

Radiative forcing (RF) is the heating of the Earth due to the Sun's radiative heat being captured in the Earth's atmosphere, and depending on the presence of contrails, RF can vary significantly. Since 1750, the total amount of anthropogenic RF is 2.63 watts per square meter - the equivalent of heating the Earth's atmosphere by approximately 2°C [2].

The Intergovernmental Panel on Climate Change (IPCC) projects that RF due to aviation-based emissions will increase significantly. Of all emissions from air travel, contrails are believed to be the largest contributor to RF [2]. Due to a fair level of scientific understanding, contrails have an extremely high variance in the levels of RF, and could potentially contribute to upwards of four to five times as much RF as CO_2. The RF contributions of different aviation based emissions is displayed in Figure 1 [2].

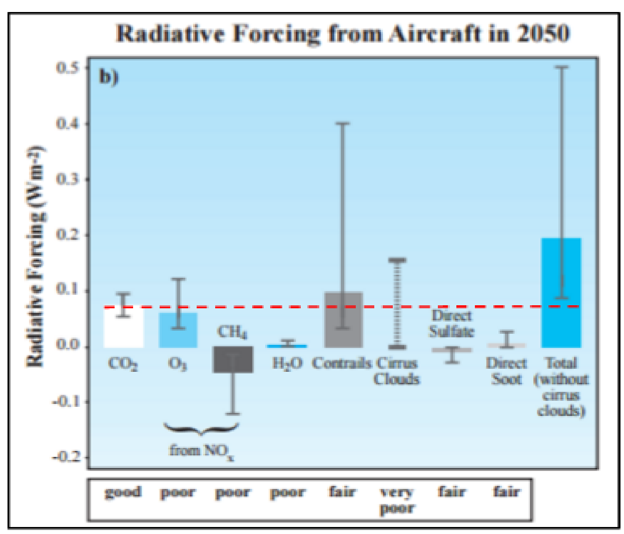

FIGURE 1:
IPCC CHART OF RF CONTRIBUTIONS OF AVIATION EMISSIONS [2]

II. STAKEHOLDER ANALYSIS

A. Airlines

Airlines are the companies that own aircraft and employ pilots and other personnel. The main goal of airlines is to minimize operating costs to increase profit as they provide safe transportation to civilians while abiding by regulations put forth by the FAA and other regulatory agencies. Some airlines put a higher importance on deploying environmentally friendly practices while others are more concerned with lowering costs.

B. Citizens

Citizens typically have two perspectives within the context of air travel, as money conscious travelers and as environmentally concerned travelers. Passengers who are primarily concerned with the price of flights will frequently purchase airfare based on the lowest possible price. This type of traveler has elastic demand for price, and are sensitive to increases in airfare.

Results from a 2013 study done by Robert J.P. Mayer shows that 95% of environmentally concerned travelers are willing to pay more for a ticket to offset aviation emissions [3].

C. Federal Aviation Administration (FAA)

The FAA is the main organization in charge of managing domestic flight operations and overseeing regulations. Regulation is done through the licensing and certification of personnel, equipment, and procedures to ensure that everything is performing up to the standards set by the FAA. All aspects of flight must be in compliance of FAA standards as found in the Code of Federal Regulations.

D. Congress

Congress has several responsibilities within the air transportation system. Most notably, they oversee and approve of funding for the FAA, Environmental Protection Agency (EPA), and other government organizations that regulate or interact with the air transportation system. Congress also has the ability to pass legislation that can directly or indirectly affect the air transportation enterprise, or other stakeholders.

E. Stakeholder Tensions

There are several tensions that exist between the four main stakeholders previously listed. With an increased focus on green aviation practices, legislation created by congress will increase the operating costs of airliners. If the operating costs of the airliners increase, then ticket prices will increase yielding a heightened ticket price. This limits the number of citizens that can afford to fly and would yield a lower load factor – meaning fewer people are able to travel and airlines would lose money.

F. Win-Win Scenario

A win-win scenario can exist if airlines enact an environmental conservation strategy that appeals to passengers enough to boost ticket sales and increase revenue. This would establish feasibility for the airlines to invest without requiring additional funding subsidies from congress. Additionally this would help boost an airline's reputation among travelers as they entrust that the airline is proactive about helping care for the environment.

III. PROBLEM AND NEED STATEMENTS

According to the IPCC, aviation based RF is projected to increase by 280% from 1992 to 2050 [2]; this correlates with a 2°C increase in temperature. There is currently no system within the National Airspace System (NAS) to monitor and manage contrail production despite the belief that they are the largest contributor to aviation-based RF. Without an immediate solution to mitigate contrail generation, RF will increase with the 2.1% per year average growth of the domestic air transportation enterprise. A system needs to be developed to utilize the opportunity in aircraft contrail generation optimization to prevent radiation from entering the Earth's atmosphere and allow outgoing heat to escape. This functionality will reduce net RF and improve quality of life by reducing the negative effects of global warming.

IV. CONOPS

Controptimal is a system that encompasses a developed simulation in order to optimize when contrails are formed based on ISSR presence and time of day to reduce net RF. Airline dispatchers will utilize Controptimal to help develop flight plans to minimize fuel burn, flight duration, and net RF. The DSS is a web-based tool that will aide airlines in finding routes that abide by FAA regulations and are easily integrated into the National Air Space (NAS).

V. METHODOLOGY & SIMULATION

Optimization of contrail generation to reduce net RF was carried out via simulation of alternative flight paths to compare performance metrics to a base route. This baseline route used the fuel-efficient Great Circle Distance (GCD) at FL 350 (Flight Level: 35,000 ft).

The first part of the simulation tested nine altitudes, from FL 290 to FL 450 in intervals of 2,000ft, in order to test if alternative routes had lower net RF values than the baseline. The nine routes were selected based on limitations of the NAS and Air Traffic Control (ATC) standards. Each of these routes was then assigned an altitude to fly at for the duration of the simulation. Since these routes account for weather, their performances were quantified with an increased or decreased RF value.

Following the initial simulation, Controptimal then used a case study flight, timestamped '2015-08-16 09:00.' This case study utilized the same methodology but instead implemented optimized network simulation rather than a constant flight level. This network utilized fuel burn, duration, and RF metrics for paths between nodes. The shortest path for net RF was then computed along with other relevant metrics. These values were then exported to a Comma Separated Values (CSV) file for tradeoff analysis. The purpose of this case study was to test whether the utilization of real-time weather data would have a higher utility than that of the top performing flight from the initial simulation.

As shown in Figure 2, the overall simulation model utilizes inputs of the GCD and historical weather to capture all aspects of the dynamic models. Structurally, the model is comprised of the trajectory track (blue) and the weather track (green) that utilized the mentioned inputs. The outputs of the model include a cost breakdown, tradeoff analysis, baseline comparison, and ultimately a new flight plan that will be sent to airline dispatch.

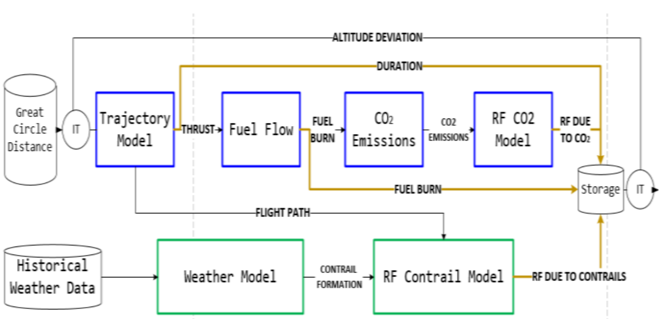

FIGURE 2:
SIMULATION MODEL

A. *Trajectory Model*

The aircraft's trajectory is modeled in two different states. Table I displays all variables used in the trajectory model.

The first two equations listed in Table II determine the thrust needed at climbing and cruising states, respectively, while the last equation determines the drag force experienced by the aircraft, regardless of trajectory state [4].

TABLE I
AIRCRAFT TRAJECTORY VARIABLES

Symbol	Name	Units
T	Thrust	N
D	Drag	N
W	Weight	kg
γ	Flight Path Angle	Degrees
α	Angle of Attack	Degrees
C_D	Coefficient of Drag	Unitless
ρ	Air Density	Slug/ft^3
V_{TAS}	True Air Speed	ft/s
S	Wing Platform Area	ft^2

TABLE II
AIRCRAFT TRAJECTORY EQUATIONS

CLIMB AT CONSTANT VELOCITY	CRUISE, CONSTANT VELOCITY	COEFFICIENT OF DRAG
$T = \frac{(D + \sin\gamma)}{\cos\alpha}$ (1)	$T = D$ (2)	$D = \frac{C_D \rho V_{TAS}^2 S}{2}$ (3)

B. *Fuel Flow*

BADA aircraft performance data was used to calculate the fuel burn during the climb, cruise, and descent phases of flight. This data is specific to the Boeing 737-800 model however, in other cases, the model is robust enough to handle other aircraft.

C. *CO_2 Emissions*

Carbon dioxide emissions were calculated by multiplying the fuel burn with the coefficient *c* [5].

$$c = 3.176\left(\frac{kg\ of\ CO2\ released}{kg\ of\ fuel\ burned}\right) \tag{4}$$

D. *Radiative Forcing of CO_2*

The CO_2 based RF of a given flight was determined by relating the mass of CO_2 released to a known ratio of CO_2 release and RF caused. In taking time into consideration regarding CO2 and its negative impact over time, multiplier of 2.8 was found to be necessary to model CO2 accurately [6].

$$RF_{CO_2} = \left(\frac{CO_2}{641\ Tg\ CO_2}\right)\left(30\,\frac{mW}{m^2}\right) * 2.8 \tag{5}$$

E. *Weather Model*

A Monte Carlo simulation was conducted on one year of recorded weather data between Dulles International Airport (IAD) and Orlando International Airport (MCO) provided by the National Oceanic and Atmospheric Administration (NOAA). The simulation uses temperature and relative humidity (%) as inputs. ISSR formation was defined by having a temperate less than -40C and a relative humidity with respect to ice of 50%. The results of this simulation determine the probability of an ISSR along a flight path.

After analyzing the summer months (May-August 2015) of the data set, it was found that ISSRs cover about 43% of the airspace between 29,000 and 45,000 feet along the flight path. The average floor altitude for an ISSR is 37,000ft and an average ceiling of 43,000ft. ISSRs are most likely to occur between 39,000 and 41,000 feet, with 67% coverage in that altitude range. The lower altitudes are not as probable to host contrail formation. This can be illustrated in Figure 3. The contrail coverage found in this analysis was verified by subject matter experts [7, 8]. This analysis was performed exclusively during the summer months because that is where the highest probability of ISSR coverage occurs due to more favorable atmospheric conditions, most notably higher relative humidity.

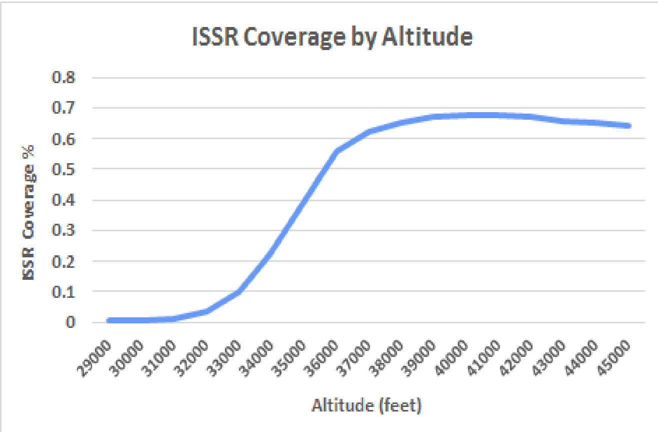

FIGURE 3:
THE LIKELIHOOD OF ENCOUNTERING A CONTRAIL AT DIFFERENT ALTITUDES. THESE NUMBERS WERE AVERAGED OVER ALL DATA POINTS AT EACH ALTITUDE OVER ONE YEAR. FL 390 YIELDS HIGHEST PROBABILITY OF CONTRAIL FORMATION.

F. Contrail Model

Scientist H. Appleman defined the atmospheric conditions needed to generate contrails in the 1950's [9]. The likelihood of contrail generation varies based on changes in air pressure (altitude), temperature, and relative humidity. The two most important conditions that must be met in order to for contrails is as follows: air temperature of -40°C or colder, and relative humidity with respect to ice of 50% or higher. At most cruising altitudes, the temperature is always below the -40°C temperature ceiling whereas humidity is more likely to vary based on location and season.

The radiative properties of a contrail are determined by the contrail's lifetime, spreading rate, microphysical properties, albedo, and the solar zenith angle. It should be noted that contrail spreading rate and contrail lifetime are factors that influence the size of the contrail and potential exposure to the sun. Contrail lifetime can be examined by its four regimes: jet regime, vortex regime, dissipation regime, and diffusion regime [10]. Each regime correlates with a time in the lifecycle of a contrail.

G. Radiative Forcing Model

There are two components to contrail-based RF: shortwave and longwave. Shortwave RF is due to the reflection of solar radiation off of a contrail -- this is known as negative RF and has a net cooling effect on the Earth's atmosphere. Conversely, longwave RF occurs when radiation is absorbed in the Earth's surface. This is defined as positive RF and has a net heating effect on the Earth's atmosphere. The net RF of a contrail is the sum of its longwave and shortwave radiation. Contrails act as a barrier and inhibit the movement of both types of RF.

The RF for both longwave and shortwave were calculated. Outgoing longwave radiation (OLR) and solar direct radiation (SDR) data was obtained from NOAA sources, temperature data (T) was collected from the Rapid Refresh (RAP) data source, and the solar zenith angle (μ) was obtained hourly from a United States Navy database [11]. All other parameters were estimated by Schumann's RF model [12]. These parameters were held constant while obtained values were varied based on weather data inputs.

$$RF_{LW} = [OLR - k_T(T - T_0)] \times \{1 - \exp[-\delta_\tau F_{LW}(r_{eff})\tau]\} E_{LW}(\tau_c) \quad (6)$$

$$RF_{SW} = -SDR(t_A - A_{eff})^2 \alpha_c(\mu, \tau, r_{eff}) E_{SW}(\mu, \tau_c) \quad (7)$$

TABLE IIII
LONGWAVE AND SHORTWAVE RADIATION VARIABLES

Symbol	Definition
OLR	Outgoing Longwave Radiation
k_T	Atmospheric Temperature
T	Contrail Temperature
δ_τ	Schumann Approximated Parameter
F_{LW}	Long Wave Factor
r_{eff}	Effective Radius of Contrail Ice Particle
τ	Optical Depth
E_{LW}	Schumann Approximated Parameter
E_{SW}	Schumann Approximated Parameter
SDR	Solar Direct radiation
t_A	Schumann Approximated Parameter
A_{eff}	Effective Albedo
α_c	Schumann Approximated Parameter
μ	Solar Zenith Angle

H. Simulation

Simulation involved iteration through the multi-track model for 615 takeoff times and each takeoff time was tested with all nine candidate flight plans. Each point along the path was tested to determine if an ISSR was present. If so, the contrail RF with that point's given temperature was calculated. Each of these factors was outputted to a CSV file for later tradeoff analysis.

For the case study simulation, the fuel burn, duration, and RF values were calculated for each arc between nodes using the Matlab-based flight model. These were exported into a CSV file and imported into the Python-based network optimization script. The Python package NetworkX was utilized to build and populate the network as well as compute the shortest path for radiative forcing. The fuel burn and duration were also computed and exported for tradeoff analysis.

I. Objectives Hierarchy

In order to find the most optimal route in terms of environmental friendliness and airline usage, a value hierarchy was derived via stakeholder feedback that included a tradeoff between: net radiative forcing, fuel burn, and flight duration. Fuel burn and duration of the flight were considered to be preferentially independent because airlines and pilots consider the two fields independent of one another and judge this on a flight by flight basis. The stakeholders who provided feedback were FAA employees and a commercial airline pilots.

In speaking with stakeholders regarding tradeoffs relevant to the system, it was derived that tradeoff should consist of factors shown in Figure 4. The weights each of these values were elicited via the tradeoff weights and ranking methods; the weights were 0.45, 0.36, and 0.18, respectively. From there, decreasing linear single value dimension functions were constructed for net RF and fuel burn while flight duration yielded a negative exponential single dimension value function. In all cases, a lower value for that specific field correlated with a higher utility.

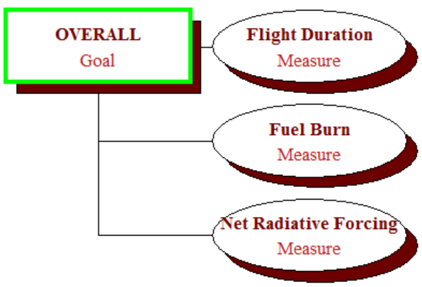

FIGURE 4:
THE VALUE HIERARCHY

VI. RESULTS

Results from the simulation indicate that by deviating from the planned altitude (FL 350) proved to decrease in radiative forcing while adhering to FAA NAS traffic flow protocol. More specifically, it was found that two of the nine flight plans decreased the net radiative forcing by 76% and 94%, by flying at FL 330 and FL 310, respectively. The latter had a net RF value of 3.97 x 10^{-7} W/m^2. Figure 5 shows the tradeoffs between the nine tested flights. While factoring fuel burn and flight duration, FL 310 flights had the highest utility, mainly due to the significant reduction in net RF associated with the flight path. Figure 5 should be interpreted as follows: a larger red bar represents a lower route net RF, a larger green bar represents lower route fuel consumption, and a larger blue bar represents a shorter flight duration.

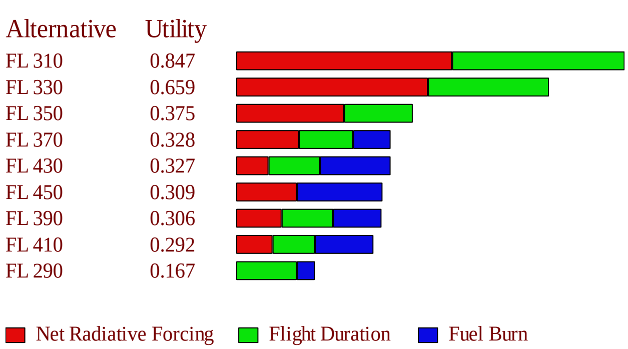

FIGURE 5:
SIMULATION ROUTE UTILITIES

Figure 6 demonstrates approximately 200 iterations of the tradeoff simulation, more specifically the RF due to contrails of the baseline (FL 350) and the highest average utility route (FL 310). Although the FL 350 flight had extreme ratings of negative RF, it had positive contrail RF 90% of the time. Conversely, the FL 310 path is more consistently close to 0 W/m^2 and had a much lower variance. This information suggests that contrail optimization strategies could be realistically used to reduce net RF due to aviation.

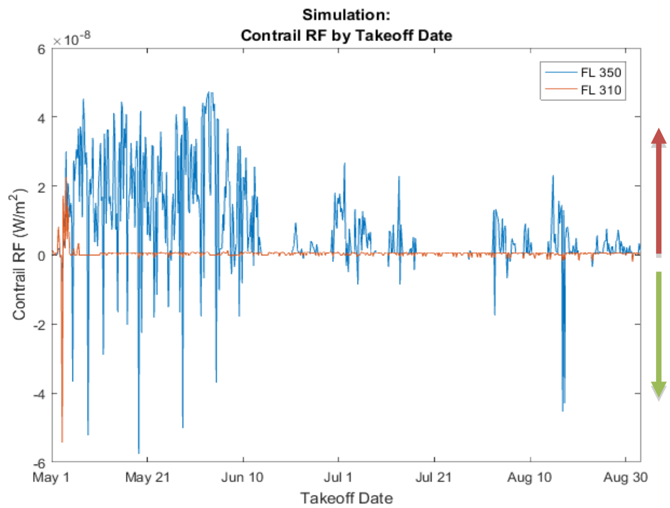

FIGURE 6
NET RF OF FL350 VS FL310. NOTE THAT THE POSITIVE NUMBERS REPRESENT HEATING WHILE THE NEGATIVE NUMBERS REPRESENT COOLING AND ARE MORE IDEAL.

As discussed, since the results of the initial simulation proved favorable, an optimized network simulation was developed to test a specific flight given the weather conditions at altitude for that day and time. The previous network created flight paths based on pre-determined altitudes. In the optimized network, flight paths are generated based on minimizing radiative forcing by varying the decision variable of altitude. The paths are then subjected to the value hierarchy using the same weights as the first simulation.

When the case study flight was analyzed, it was found that a savings even greater than the top performing flight paths decreased RF. The simulation found an optimal route that was at an originating altitude of FL 330 and then ascended to FL 380 roughly one hour into the flight. By flying this trajectory, net RF was decreased by 94%, increased fuel burn by 3%, and with roughly a 4-minute increase in flight time.

In addition to the tradeoff analysis, a cost breakdown was also outputted by the system. The excess cost per seat was computed based on the excess fuel burn needed for the new route. From the cost breakdown output, it was found that FL 310 saw only $0.81 increase in cost per seat based on a B737-800 capacity. However, if preferable, an airline could shift the added cost to first class tickets due to price inelasticity of that category. This would result in an increase of $8.16 per first class seat, and follows the potential win-win scenario as previously mentioned.

VII. Business Case

A business case was developed for the web-based Controptimal DSS to satisfy two gaps in the current market: (1) the availability of aviation-based “green systems”, and (2) the public knowledge of environmental conservation efforts taken by airlines. The tool will be used by airline dispatchers to generate contrail-optimal flight plans.

Controptimal will be made available to airlines as a yearly subscription service. A subscription gives individual airline dispatchers password access to Controptimal’s online service. With this password, the dispatcher can create a flight plan through Controptimal for any flight that they are responsible for.

Routes that frequently use the most optimal flight plan can earn a rating of gold, silver, or bronze, based on the percentage of contrail optimal flight plans that are flown. This information will be confirmed and collected via flight tracking. The rating system mentioned will be prominently displayed on ticket booking websites in order to inform the customers of an airline’s flight planning habits in terms of environmental-friendliness.

Airlines will benefit from Controptimal through improved public reputation with respect to environmental conservation efforts, resulting in increased ticket sales and revenue. This benefit to the airlines outweighs the small increase in fuel burn costs mentioned in the results section.

The fixed yearly costs of running Controptimal as a business, including office space rent, employee salaries, and equipment, are approximately $860,000. Variable costs amount to $60,000. The subscription rate for an individual dispatcher password is $100,000 per year of service. If 15 password subscriptions are sold in the first year of business with a 20% growth rate, the break-even point will be reached early in the 3rd year of business. Growth rates of 25% (optimistic) and 15% (pessimistic) adjust this break-even point by ± 6 months. Under the 20% growth rate, the 5 year ROI is 14.1% and increases by approximately 7% per year onward.

VIII. Conclusion

After testing four months of simulated flight paths, there is sufficient evidence to prove that flying routes that reduce net RF while remaining fuel-efficient is feasible. On average, there was an 85% decrease in net RF when comparing most optimal altitude with the baseline altitude. In addition, the lower FL 310 had a lower variance in contrail RF as compared to the FL 350 baseline. As aircraft engines become more and more efficient, contrail mitigation will become a much larger aviation related environmental factor. With expansion of this research to the national level comes an opportunity to design a more environmentally sustainable National Air Space.

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