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Cruise Fuel Reduction Potential from Altitude and Speed Optimization in Global Airline Operations*

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This paper examines the potential fuel efficiency benefits of cruise altitude and speed optimization using historical fight path records. Results are presented for a subset of domestic US flights in 2012 as well as for long haul flights tracked by the European IAGOS atmospheric research program between 2010 and 2013. For a given lateral flight route, there exists an optimal combination of altitude and speed. Analysis of 217,000 flights in domestic US airspace has shown average potential savings of up to 1.96% for altitude optimization or 1.93% for speed optimization. International flights may be subject to different airline and/or air traffic management procedures and constraints. Examination of 3,478 long-haul flights, representing three airlines and a single aircraft type over a four-year period, indicates average potential savings of up to 0.87% for altitude optimization or 1.81% for speed optimization. This is equivalent to a mean fuel savings of 905 pounds and 1981 pounds per flight, respectively. Due to the limited sample set for long haul flight records, conclusions from this stage of the international study are limited to the specific airlines and aircraft types included in the IAGOS measurement program.

I. BACKGROUND

Environmental and economic concerns provide motivation for fuel consumption reduction in air transportation. There are various techniques to control fuel-related environmental impact with varying implementation timelines and potential benefits. These include new aircraft technology (decade-scale implementation, high cost), retrofits to existing aircraft (multi-year implementation, medium cost), alternative jet fuel and propulsion technology (decade-scale implementation, high cost), and operational mitigation (rapid implementation, low cost) [1]. Operational mitigations are useful due to the potential for rapid implementation and low capital expenditure, although the long-term benefit is generally less than other technology-driven solutions. Prior research in academia and industry has identified potential operational mitigations. For example, Marais et al. proposed 61 specific operational mitigations with implementation timelines in the 5-10 year range [2]. Of these, eight mitigations dealt with opportunities in cruise altitude and speed optimization (CASO).

The fuel efficiency of an aircraft at any point along its flight path is a function of weight, altitude, speed, wind, temperature, and other second-order effects. At a fixed weight, there exists a combination of speed and altitude at which instantaneous fuel efficiency is maximized, as shown in Figure 1 for a typical widebody long-range airliner. For a full flight, this becomes an optimal sequence of speeds and altitudes to minimize fuel consumption [3]. The speed and altitude at which aircraft are actually flown may differ from this optimal point for a variety of operational and practical reasons. Integrated fuel consumption depends on effective trajectory planning in speed and altitude as well as in lateral flight path. There are many examples in the literature demonstrating techniques and potential applications for single-flight trajectory optimization in lateral, vertical, and temporal dimensions (e.g. [4]–[11]). However, no research has demonstrated the systemwide benefits pool of such optimization concepts compared to current operating practices.

The degree to which flights may operate at optimal altitudes and speeds depends on a variety of system characteristics, including prevailing weather conditions, congestion, airline schedules, operating costs, and Air Traffic Management (ATM) technologies available on the ground and in the cockpit of participating aircraft. In domestic US operations, the suite of communication, navigation, and surveillance (CNS) technologies allows for continuous very-high frequency (VHF) radio communication, and radio-based navigation, and radar tracking. However, traffic volumes prevent unconstrained altitude selection in most areas of the country. Speed selection is driven by a combination of ATM constraints and airline operational priorities.

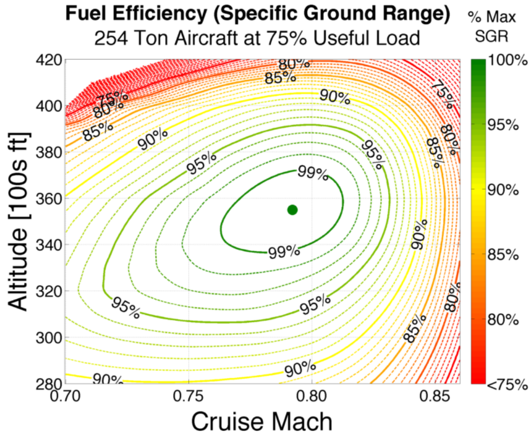

Figure 1. Instantaneous fuel efficiency of a typical long-haul aircraft at a fixed weight (calm winds, standard atmosphere)

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Long haul operations often occur over oceans and sparsely-populated land masses. Oceanic operations provide unique challenges for airlines and air traffic control due to limitations on CNS. Radar coverage does not extend over oceans, requiring non-radar procedural separation using periodic aircraft position reports [12]. As a result, minimum spacing between aircraft must be increased, climbs cannot be granted easily, speed assignments are driven by spacing rules rather than pilot request, and options for crossing flows may be limited. This results in reduced system capacity as well as limitations on flight path flexibility for airborne aircraft. However, new CNS capability currently under development or in early phases of implementation (such as datalink communication, GPS, and satellite-based Automatic Dependent Surveillance-Broadcast) may allow for increased flight track efficiency.

In the North Atlantic Track (NAT) system for example, speeds and altitudes are normally assigned at the entry point to the track system. Depending on airspace congestion, aircraft equipage, airline operating practices, and other factors, the aircraft is assigned an entry speed and altitude for the oceanic crossing. Until recent years, this initial clearance was maintained for the remainder of the oceanic phase. Recently, limited options for enroute climbs, descents, and speed changes have been implemented to provide greater flexibility and increased efficiency to aircraft located outside of radar coverage [13]. Air navigation service providers (ANSPs), regulators, and airlines are interested in examining the potential benefits of this new oceanic enroute speed and altitude flexibility, as well as potential benefits that could be achieved with continued CNS technology investment and procedural modification.

II. RESEARCH OBJECTIVES

A. *Development of Cruise Fuel Efficiency Evaluation Tool*

This research aims to identify potential fuel cost savings from optimized altitude and speed profiles to current operational norms. To achieve this objective, a flexible analysis tool is required to integrate historical flight tracks with aircraft performance and weather data. Such a model must allow for detailed flight-by-flight analysis of flight tracks in a variety of formats, and provide fuel burn reduction estimates for modified trajectories with optimized altitude and/or speed.

B. *Estimation of Best-Case Efficiency Benefits from CASO in Global Operations*

This objective is to extend the US Domestic CASO analysis to a variety of global operations. In order to extend the prior analysis, new data sources and associated analysis routines are required. This quantification is intended to provide a best-case fuel saving potential, or benefits pool, for altitude and speed optimization as an operational fuel mitigation strategy. With an understanding of the potential benefits to be derived from altitude and speed optimization, it becomes possible to determine reasonable levels of implementation effort and expense.

C. *Comparison of Efficiency Benefits from CASO in Domestic US and Long Haul Operations*

Prior research has demonstrated the potential benefits of CASO in domestic US operations [14]–[17]. Based on the results of the global flight analysis, it is desirable to compare the operational efficiency of long-haul operations to shorter stage lengths within the congested domestic US national airspace system (NAS).

III. METHODOLOGY

A. *General Methodology*

This analysis method compares historical as-flown flight records to modified versions with optimized speed and altitude profiles. Figure 2 shows the high-level framework used to determine the benefits of optimized trajectories. The method combines data from several sources to generate fuel burn estimates and optimized trajectories on a flight-by-flight basis. For each flight, the method requires input data for:

- Aircraft fuel burn performance as a function of weight, altitude, and speed
- Flight tracks, including latitude/longitude traces, altitudes, and timestamps
- Historical weather, including wind vectors and temperatures at latitudes, longitudes and altitudes of interest

B. *Aircraft Performance Data*

Lissys Piano-X, a commercial off-the-shelf aircraft performance software package, provides aircraft performance data. The performance database in Piano-X is derived from flight physics, tuned using data from airlines and manufacturers. The validation process for each aircraft definition file is summarized in development notes included with the model [18]. The instantaneous point performance module of the tool allows calculation of fuel efficiency, among other parameters, at various points in cruise flight. Given an input state vector of speed, altitude, and weight, the model outputs a clean-configuration steady state performance vector including aerodynamic coefficients, performance margins, and emission metrics. This output vector includes specific air range (SAR, air range per pound of fuel consumption), which can be used in conjunction with wind data to calculate specific ground range (SGR, ground range per pound of fuel consumption).

Piano-X cruise performance outputs were compared against Eurocontrol's Base of Aircraft Data (BADA) Revision 3.6. Aircraft cruise fuel calculations within this version of BADA use a simplified parametric approach for aerodynamic and propulsive performance, incorporating a total of five aircraft-specific coefficients for the thrust and fuel consumption sub-models [19]. This simplified approach may reduce the accuracy of the model for high-fidelity cruise calculations [20]. Direct comparison of SAR contours from Piano-X and BADA for three aircraft types showed reasonable agreement near optimal cruise speed and altitude operating points. Averaging SAR at all combinations of altitude and speed in three weight cases, the following differences between Piano-X and BADA were observed for three typical aircraft types:

- Regional Jet: SAR in BADA larger by 2.69%
- Narrowbody: SAR in Piano-X larger by 1.76%
- Widebody: SAR in BADA larger by 5.82%

Piano-X SAR contours showed stronger efficiency penalties far from optimal speeds and altitudes, particularly at high aircraft weights. Therefore, the selection of Piano-X as an aircraft performance model may slightly overestimate fuel burn reduction from CASO compared to a similar analysis with BADA Revision 3.6.

While the full Piano-X aircraft database includes 465 types and aircraft sub-variants, this analysis used a subset of 47 aircraft types that occur most frequently in US Domestic and North Atlantic Oceanic high-altitude operations. The resulting aircraft performance database differentiates aircraft types by variant. For example, the Boeing 737-800 and Boeing 737-900 use separate performance models, but a 737-800 with winglets shares its performance model with the base model. This level of discretization mirrors the level of aircraft type information available in most flight path records, where aircraft sub-varieties and structural modifications are normally not provided.

The calculation of instantaneous fuel efficiency in Piano-X is performed at one-minute intervals along each cruise segment and integrated to yield full-trajectory fuel burn. Fuel burn during climb and descent is corrected using the component of total aircraft weight acting along the flight path vector. This force component is treated as a direct scalar on thrust and instantaneous fuel consumption.

C. *Flight Track Data*

For domestic US flights, track data was obtained from the FAA's Enhanced Traffic Management System (ETMS). ETMS stations display and log fused flight track records from the full network of Airport Surveillance Radars (ASRs). Logged ETMS records provide historical flight trajectory data for flights inside North American airspace operating under instrument flight rules. Data fields include airline, flight number, aircraft type, latitude, longitude, altitude, groundspeed, and time. Parameters are logged at 60-second intervals, nominally covering all flight phases inside the coverage area from initial climb to final descent.

The domestic sample set consisted of over 217,000 flights from 2012. These flights occurred on 18 days throughout the year, representing a variety of weather conditions and system congestion states. The analysis included only those 47 aircraft types included in the aircraft performance model, including the most commonly-used single aisle and twin aisle jet aircraft. Only those flights with cruise segments above 28,000 feet were included in the sample.

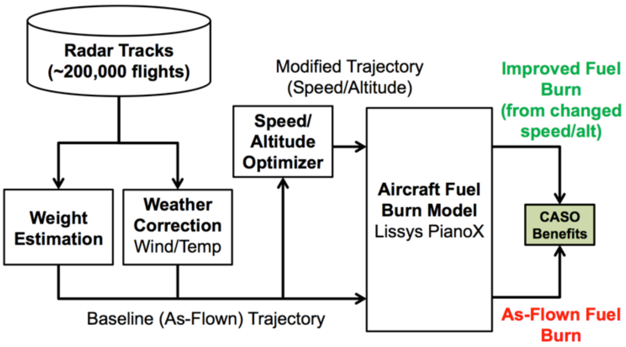

Figure 2. High-level analysis framework for comparing baseline and optimized trajectories

For international flights, track data was obtained from a European aircraft monitoring program, In-service Aircraft for a Global Observing System (IAGOS), a follow-on program to the earlier Measurement of Ozone and Water Vapour on Airbus in-service Aircraft (MOZAIC) initiative. For this program, a fleet of 10 Airbus A340-300s and A330-200s have been outfitted with atmospheric instrumentation packages and a recording system that interfaces with aircraft navigation systems. The lateral tracks are recorded directly from aircraft navigation systems during flight, from takeoff to touchdown. Data columns include latitude, longitude, altitude, and a variety of weather parameters. Native temporal resolution is four seconds, which is down-sampled to one minute resolution for CASO calculations.

The sample set used for this analysis was limited, consisting of 3,763 flights from three airlines and five individual Airbus A340-300s. The flights occurred between 2010 and 2013. The geographic coverage of this sample set is shown in Figure 3.

The objective of this analysis was to determine the impact of trajectory optimization in the cruise phase of flight. The beginning of the cruise phase was taken to be the first level segment of flight lasting at least 10 minutes and occurring above 28,000 feet (FL280). The end of the cruise segment was the last segment meeting the same criteria. The cruise phase used for analysis was taken to be the full track segment connecting these segments, as shown in Figure 4.

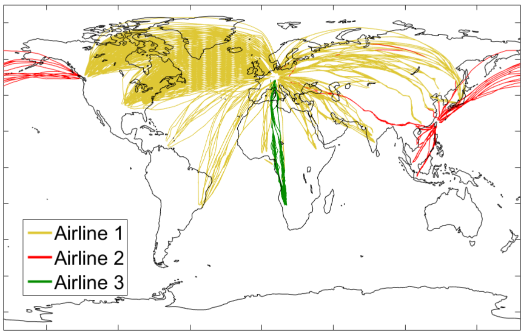

Figure 3. Flight track records from the IAGOS fleet between 2010 and 2013 (3,763 individual flights)

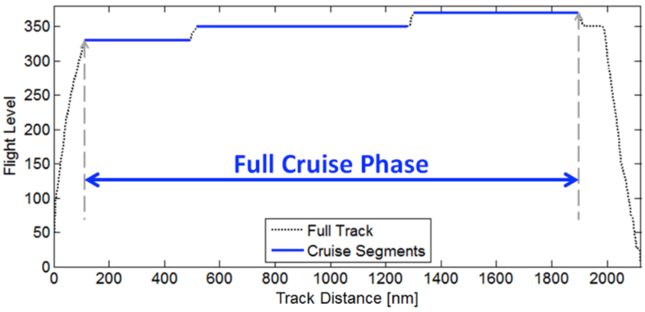

Figure 4. Illustration of cruise phase selection from full flight track

D. *Weather Data*

US domestic weather data was obtained from the National Oceanographic and Atmospheric Administration (NOAA) North American Regional Reanalysis (NARR) archive. This is a truth weather product rather than a forecast, generated by incorporating a variety of atmospheric data sources into a single coherent weather picture. Wind and temperature are provided on a 32km horizontal grid, with 29 pressure levels and 3-hour temporal update cycles. Weather conditions encountered by a flight at a specific time, location, and pressure altitude are calculated by spatial and temporal linear interpolation. The coverage area of the NARR model is shown in Figure 5. Due to the geographic extent of IAGOS tracks, a different weather model is required for extended global analysis.

Weather data outside the North American region is obtained from the NOAA Global Forecast System (GFS) archive. This model is commonly used by airline dispatchers and flight planning systems. Wind and temperature are provided on a 1-degree grid in latitude and longitude, with 26 pressure levels and 6-hour temporal update cycles. As for the domestic analysis, weather conditions at the aircraft are calculated using spatial and temporal linear interpolation.

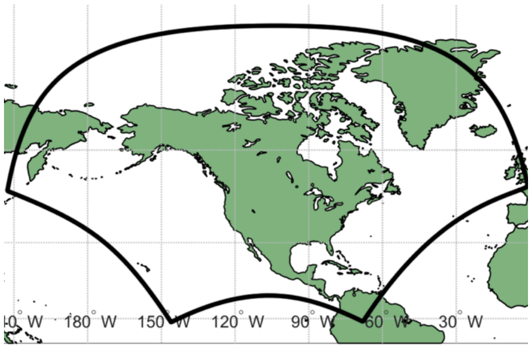

Figure 5. Geographic coverage area for NOAA NARR weather archive

E. *Weight Estimation*

Aircraft weight has a significant impact on fuel burn. However, most public flight track records do not include weight information. In order to predict fuel burn for a flight based on radar records, estimates for aircraft weight must also be generated. For this analysis, these estimates are based on data from 35,131 sample flights provided by three US airlines from operations in 2012. These samples span a variety of aircraft types, routes, and days of operations.

Based on given data, a regression surface has been developed to estimate the weight at the beginning of cruise (Top-of-Climb Weight, TOCW) as a function of the initial altitude and the total recorded flight time. Sufficient data was available to generate regression surfaces directly for 10 common aircraft types. The remaining 35 aircraft types used a hybrid regression surface that forecasted TOCW as a percentage of Maximum Gross Takeoff Weight (MGTOW) as a function of flight time. Figure 6 shows the weight estimation surface developed for one single-aisle aircraft type with the supporting data used to develop the regression.

F. *Baseline Fuel Calculation*

The baseline fuel calculator loops sequentially over each one-minute segment of the cruise phase of a flight. At each segment, the current weight of the aircraft and weather conditions at that time and location are fed into the aircraft performance model, which provides an instantaneous Specific Ground Range (SGR) for the aircraft at that location. SGR has units of fuel mass per unit distance over the ground, allowing immediate calculation of fuel burn from ground track distance. The calculation of SGR is repeated for each point along the cruise phase of a flight, updating the aircraft weight with each segment on account of fuel consumption. The as-flown fuel consumption is determined by integrating instantaneous SGR over the full flight distance.

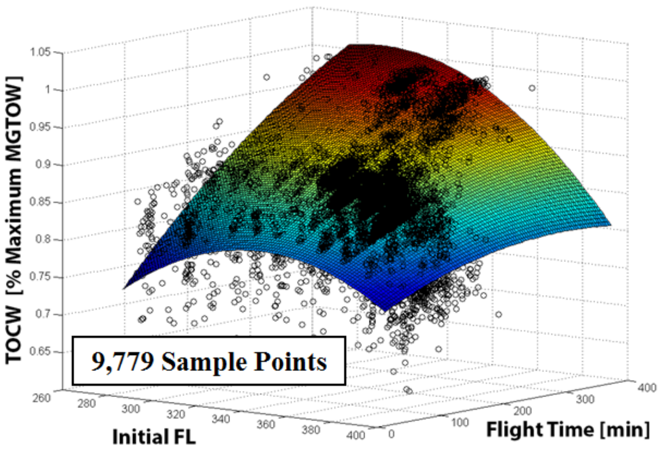

Figure 6. Weight estimation surface for one common single-aisle medium-range aircraft type

G. *Altitude Optimization*

The profile optimizer also loops sequentially over each one-minute segment of the cruise phase of a flight. At each segment, the current weight of the aircraft and weather conditions at each altitude are fed into the aircraft performance model. This process is repeated for each cruise Mach number between M0.70 and the maximum cruise Mach for the aircraft. In this manner, an instantaneous fuel efficiency surface is defined for every one-minute interval of the cruise phase, accounting for winds and temperatures.

The maximum point on this notional surface represents the combination of speed and altitude that would result in the least fuel burn for that one-minute segment of flight, accounting for local winds. Constraints in speed and altitude are easily applied by maximizing cross-sections of the efficiency surface rather than the entire space. An example SGR surface is shown in Figure 7. The shape and magnitude of these contours varies considerably as a function of aircraft type, weight, and weather.

Optimal altitude profiles are calculated using two methods. In a standard atmosphere with calm winds, the optimal altitude profile for an aircraft in cruise flight would be a steady climb. However, fluctuations in winds and temperature aloft may cause the actual minimum-fuel altitude to fluctuate. Additionally, the ATM system cannot support cruise climb operations in congested enroute airspace, so "step climb" optimizers are more realistic given altitude assignment capabilities.

The first type of improved altitude profile is the cruise climb. The cruise climb optimizer finds the best linear fit to the sequence of optimal altitude points throughout the cruise phase of the flight, resulting in a constant rate of climb or descent. Figure 8 shows a side-view of a single long-haul flight from Frankfurt, Germany (FRA) to Guangzhou, China (CAN).

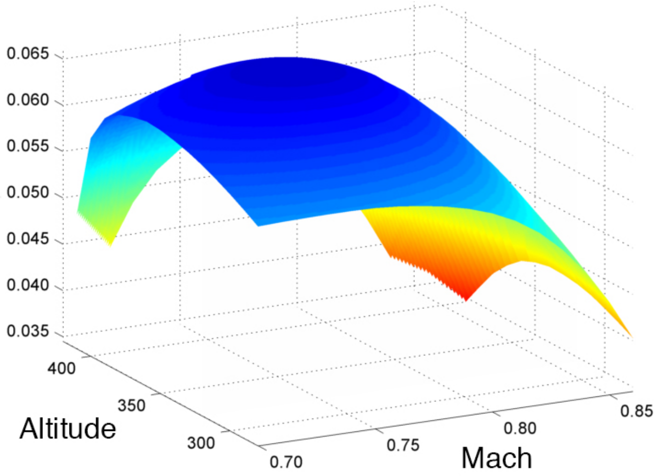

Figure 7. Instantaneous fuel efficiency surface (SGR) as a function of altitude and speed, accounting for weather

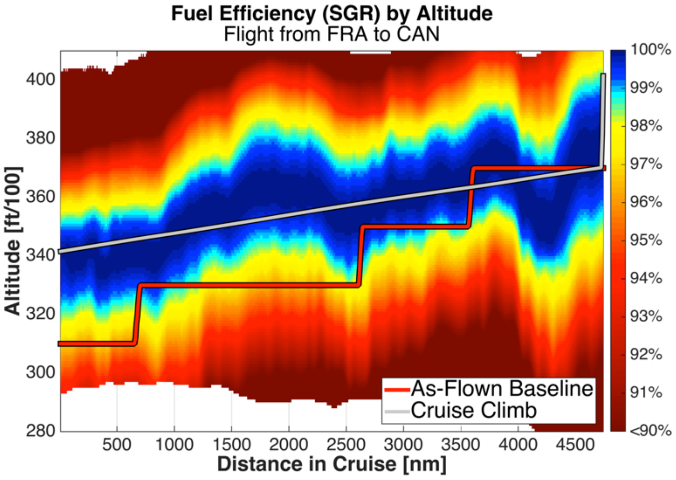

Figure 8. Side view of a typical long-haul altitude optimization profile and optimal cruise climb solution

The background colors indicate the relative efficiency at each feasible altitude along the cruise phase of flight. The blue "tunnel" indicates the band of altitudes that would have been the most fuel efficient for the flight, given weather and weight estimates. The red line indicates the baseline, as-flown altitude trajectory, while the gray line shows the output from the cruise climb altitude optimizer.

The total change in potential energy of the optimized profile is matched to the baseline by adding a climb or descent segment at the end of cruise. Therefore, the total altitude change in all optimized profiles matches the baseline. This prevents biasing the results by crediting an optimized profile for improved fuel efficiency where the actual cause of reduced consumption was a net descent relative to the baseline cruise phase.

The second type of altitude optimizer handles step climbs. The optimization algorithm is tunable to allow climbs and descents at user-specified time intervals. For the purpose of this analysis, the time limitations were set such that each altitude change was maintained for a minimum of 10 minutes (US domestic flights) or 30 minutes (long-haul flights). The optimizer uses Dijkstra's Shortest Path Algorithm to identify the optimal location for altitude changes based on these constraints. Altitude changes are not constrained to occur at equal intervals. Three variations on the step climb profile are calculated:

1. Climbs permitted to any 1000-foot altitude increment, with an altitude change of up to 4000 feet at each step. No descents permitted until the end of the cruise phase.
2. Climbs constrained to 2000-foot altitude increments based on the direction of flight, with an altitude change of up to 4000 feet at each step. No descents permitted until the end of the cruise phase.

3. Climbs or descents permitted to any 1000-foot altitude increment, with an altitude change of up to 4000 feet at each step.

Figure 9 shows a side view of the optimized 2000-foot step climb profile generated for the example long-haul flight from FRA-CAN. In terms of operational feasibility, the improved altitude profiles require more frequent altitude changes relative to current practices. For example, domestic US flights in the 2012 sample set changed altitude an average of 0.50 times per 1000 nautical miles of cruise flight. With 1000-foot step climbs, this frequency would increase to an average of 2.94 altitude changes per 1000 nautical miles. 2000-foot step climbs and flexible climb/descent profiles would require an average of 1.54 and 3.72 altitude changes per 1000 nautical miles, respectively. While the optimal profiles all require more frequent altitude change requests than current practice dictates, the profiles are operationally feasible (particularly the 2000-foot step climb profiles).

H. Speed Optimization

Two types of speed optimization are performed for this analysis based on standard airline industry reference speeds [21]:

1. Maximum Range Cruise (MRC) is the speed that minimized fuel consumption for a given mission. This speed is equivalently defined as maximizing mission range for a fixed amount of fuel.
2. Long Range Cruise (LRC) is a speed faster than MRC that achieves 99% of the efficiency of MRC, defined with respect to SGR. LRC provides a tradeoff between increased fuel consumption and shorter flight times.

The MRC speed optimizer loops over every one-minute segment of the flight and selects the optimal cruise Mach at the as-flown altitude. The optimal cruise Mach is converted to airspeed using the atmospheric temperature. The airspeed is converted to groundspeed using local winds. This procedure is repeated for every one-minute segment on the baseline track, providing both a fuel efficiency change and the corresponding change in flight time. The LRC speed optimizer functions in the same manner, but selects a faster cruise Mach such that SGR is 99% of the maximum value. The impact of this optimization on flight time is also recorded.

Both MRC and LRC speed optimization routines are designed to capture maximum benefit from speed optimization, assuming flexibility for small speed changes throughout the cruise phase of flight in one-minute intervals. These changes are driven by a combination of winds and aircraft weight. This algorithm can result in frequent speed change commands on the order of ±0.01 Mach. Such speed profiles are not operationally feasible, but do capture the maximum possible benefit from speed optimization. In practice, a reduced number of recommended speed changes would be used, each for a larger portion of the cruise segment.

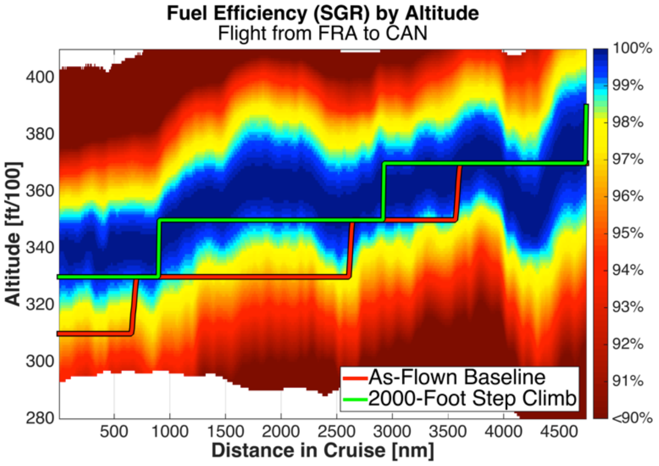

Figure 9. Side view of a typical long-haul altitude optimization profile and optimal 2000-foot step climb solution

IV. RESULTS

Optimized flight profiles and fuel efficiency impacts were recorded for each flight in the sample set for domestic US and long haul IAGOS track records. Aggregate results are presented below, separated by flight track sample set and optimization type. The mean fuel burn reduction percentages reflect changes in total systemwide fuel consumption as a result of trajectory changes, while the absolute fuel savings are the average per-flight fuel savings in units of pounds.

A. Domestic US Flights: Altitude Optimization

Table 1 shows the aggregate cruise fuel burn reduction potential for the four altitude optimization profiles in domestic US operations. A 3rd-quartile saving value is included in the table. This figure represents a threshold above which the least-efficient 25% of flights in the sample set operate.

For each of the altitude optimization methods, the mean fuel burn reduction falls between 1.75% and 1.96%. Of particular interest for system improvement are those flights operating particularly far from optimal altitude profiles. For domestic US flights, the worst-performing 25% of flights have 4.65% or greater cruise fuel reduction potential.

Table 1. Cruise Fuel Reduction from Altitude Optimization in 2012 Domestic US Flights
n=217,099

	Cruise Climb	*1000ft Step Climb*	*2000ft Step Climb*	*1000ft Step Climb/ Descent*
Mean (%)	1.87%	1.90%	1.75%	1.96%
Mean (lbs)	102 lbs	104 lbs	96 lbs	107 lbs
Median	1.17%	1.21%	1.04%	1.24%
3rd Quartile	4.72%	4.81%	4.65%	4.80%

Figure 10 shows the full distribution of fuel burn reduction potential from 2,000-foot step climb altitude optimization in domestic US operations. The distribution shows that 49.4% of flights in the sample operated less than 1% from the optimal step-altitude profile. Therefore, nearly half of flights appear to have low altitude efficiency improvement potential in domestic US operations. However, there is a pronounced tail of the distribution that represents a subset of flights that operate at altitudes significantly different from optimal.

The factors that cause certain flights to operate closer to optimal altitudes than others include airline operating practices, stage length, airspace constraints, and route characteristics. Figure 11 shows the differences in altitude efficiency between 10 large airlines in US domestic operations. The solid lines represent mainline airlines operating aircraft with more than 100-seat capacity, while the dashed lines represent regional airlines operating aircraft below that capacity. The consistent distribution peaks near 0% efficiency potential for the mainline airlines stands in sharp contrast to the broad spectrum represented by the regional airlines.

It is interesting to note the marked efficiency difference between regional and mainline airlines and aircraft types in the domestic US system. The difference is likely due to the short stage lengths normally associated with such operations. With time in cruise on each flight often less than an hour, inefficiencies that are relatively large by percentage often translate to low excess fuel burn in absolute terms. In congested enroute airspace, the incentive to match regional and short-haul flights with optimal altitudes is low.

B. Domestic US Flights: Speed Optimization

Table 2 shows the aggregate cruise fuel burn reduction potential for MRC and LRC optimal speed profiles in domestic US operations. In addition to providing aggregate results on fuel saving potential, the table provides average flight time increase as a result of speed optimization across all flights. For MRC optimization, this amounts to a flight time increase of 152s (2m 32s). For LRC optimization, the average flight time increase drops to 3s while retaining a 0.93% average fuel burn reduction potential.

Figure *12* shows the distribution of fuel saving potential from MRC speed optimization in US domestic operations. Similar to the results shown in Figure 10 for altitude optimization, many flights operate far from optimal speeds. For MRC speed optimization, the 25% of flights with the largest potential fuel burn benefit all have a reduction potential greater than 2.83%.

One strength of the domestic US analysis relative to the IAGOS long haul track set is the wide diversity of aircraft types and airlines represented in the sample set. This ensures a broad representation of system characteristics and minimizes the change of highlighting specific airline procedures. For this reason, it is possible to perform decomposition of the result set to test hypotheses about the importance of factors such as ATM infrastructure, airspace congestion, weather, airline policy, and pilot technique on fuel efficiency.

Table 2. Cruise Fuel Reduction from Speed Optimization in 2012 Domestic US Flights
n=217,099

	Maximum Range Cruise	*Long Range Cruise*
Mean (%)	1.93%	0.93%
Mean (lbs)	105 lbs	51 lbs
Median	1.24%	0.39%
3rd Quartile	2.83%	1.82%
Average Flight Time Increase (s)	152 s	3 s

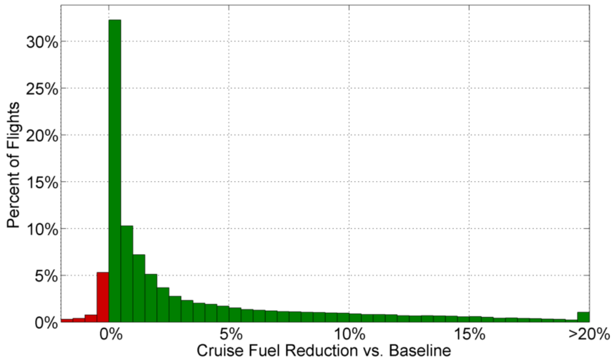

Figure 10. Distribution of fuel efficiency benefits from 2000-foot step climb altitude optimization in domestic US operations (n=217,099)

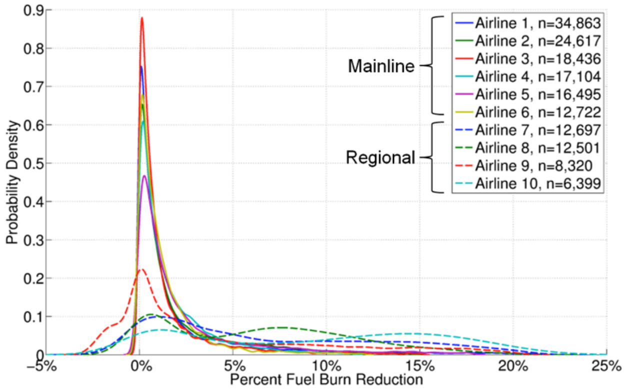

Figure 11. Distribution of fuel efficiency befits from 2000-foot step climb altitude optimization in domestic US operations aggregated by airline

C. IAGOS Long Haul Flights: Altitude Optimization

Table 3 shows the aggregate cruise fuel burn reduction potential for the four altitude optimization profiles in the IAGOS flight operations sample set between 2010 and 2013.

For this sample set, the potential percentage benefits are lower than those in domestic US operations by approximately 1%. The absolute fuel saving potential per flight, however, is nearly 8 times larger than for the domestic analysis. Due to the long stage lengths and larger aircraft types used in most long-haul operations, small percentage gains in efficiency can have larger impacts on absolute fuel consumption.

Figure *13* shows the distribution of fuel burn reduction potential from 2000-foot step climb optimization in the IAGOS long-haul sample set. With respect to percentage cruise fuel burn reduction potential, 78.6% of flights in this sample operated within 1% of the optimal altitude step profile.

The high average efficiency in the MOZAIC set may be driven by airline operational strategy or aircraft characteristics rather than inherent differences with long-haul operations. The sample set consists of 3,478 total flights operated by three airlines, all with the Airbus A340-300. Table 4 shows the difference in mean altitude efficiency between the airlines. Clearly, Airline 1 dominates the results, comprising 78% of all operations recorded. It also appears to operate closest to optimal altitudes of the three airlines, potentially skewing results toward lower benefits relative to industry averages.

D. IAGOS Long Haul Flights: Speed Optimization

Table 5 shows the aggregate cruise fuel burn reduction potential for MRC and LRC optimal speed profiles in the IAGOS global flight operations sample set between 2010 and 2013. The table also shows that full implementation of MRC speed profiles would have increased average flight times by 604s (10m 4s) while full implementation of LRC speed profiles would have reduced average flight times by 102s (1m 42s).

The percentage benefits from speed optimization in this sample set are similar to those in the domestic US analysis, although the absolute benefits are larger by nearly 20 times. Figure 14 shows the distribution of fuel saving potential from speed optimization in the IAGOS sample set. The high-benefits tail of the distribution is more pronounced than for the altitude optimization, indicating that more flights in this sample operated far from optimal speed than far from optimal altitude.

As was observed in the altitude optimization results, there were differences between the three airlines in the sample set in terms of potential benefits from speed optimization. Table 6 shows that Airline 1 and Airline 3 shared similar efficiency profiles, while Airline 2 operated closer to fuel-optimal speeds.

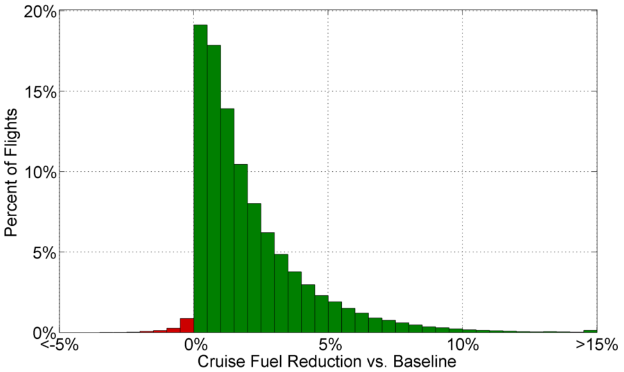

Figure 12. *Distribution of fuel efficiency benefits from MRC speed optimization in domestic US operations (n=217,099)*

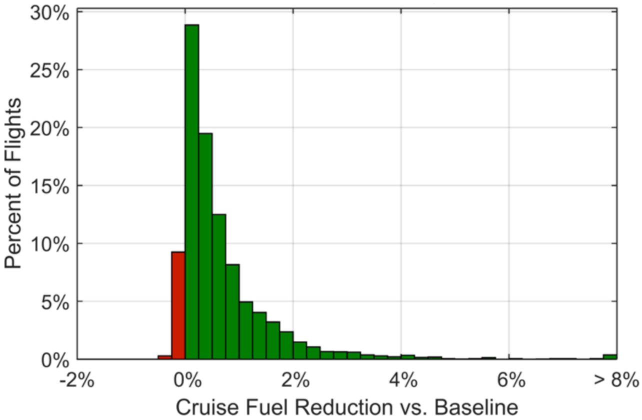

Figure 13. *Distribution of fuel efficiency benefits from 2000-foot step climb altitude optimization in IAGOS global operations (n=3,478)*

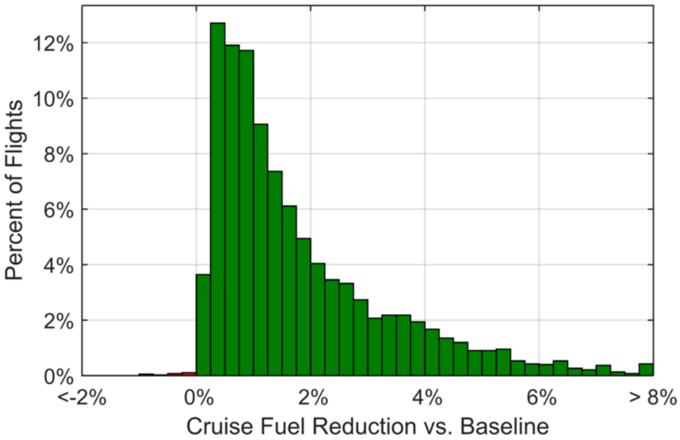

Figure 14. Distribution of fuel efficiency benefits from MRC speed optimization in IAGOS global operations (n=3,478)

Table 3. Cruise Fuel Reduction from Altitude Optimization in IAGOS Global Flight Operations (2010-2013)
n=3,478

	Cruise Climb	*1000ft Step Climb*	*2000ft Step Climb*	*1000ft Step Climb/ Descent*
Mean (%)	0.78%	0.85%	0.65%	0.87%
Mean (lbs)	810 lbs	883 lbs	682 lbs	905 lbs
Median	0.50%	0.58%	0.39%	0.60%
3rd Quartile	1.02%	1.07%	0.88%	1.10%

Table 4. Mean Cruise Fuel Reduction from Altitude Optimization in IAGOS Global Flight Operations (2010-2013)

	Airline 1 n=2,713	*Airline 2 n=146*	*Airline 3 n=619*
Cruise Climb	0.72%	1.14%	0.92%
1000ft Step Climb	0.79%	1.19%	1.01%
2000ft Step Climb	0.60%	1.00%	0.79%
1000ft Step Climb/Descent	0.81%	1.20%	1.03%

Table 5. Cruise Fuel Reduction from Speed Optimization in IAGOS Global Flight Operations (2010-2013)
n=3,763

	Maximum Range Cruise	*Long Range Cruise*
Mean (%)	1.81%	0.89%
Mean (lbs)	1891 lbs	933 lbs
Median	1.27%	0.34%
3rd Quartile	2.48%	1.56%
Average Flight Time Increase	604 s	-102 s

Table 6. Mean Cruise Fuel Reduction from Speed Optimization in IAGOS Global Flight Operations (2010-2013)

	Airline 1 n=2,713	*Airline 2 n=146*	*Airline 3 n=619*
MRC	1.84%	0.83%	1.83%
LRC	0.93%	-0.07%	0.93%

V. CONCLUSION AND FUTURE WORK

This analysis shows potential for fuel burn reduction in both US domestic and long-haul operations relative to today's baseline by modifying cruise altitudes and speeds. Results for domestic US operations indicate potential average fuel savings between 1.75% and 1.96% for altitude optimization and between 0.93% and 1.93% for speed optimization. For the small subset of long haul operations examined in this study, potential benefits from altitude range from 0.65% to 0.87%. Benefits from speed optimization range from 0.89% to 1.81%. Even with a slightly lower average percent-based efficiency benefit, the absolute fuel savings on a per-flight basis are significantly higher in long haul operations relative to domestic US flights. In this report, results are not presented for simultaneous optimization of speed and altitude profiles. Such optimization is possible using graph search methods similar to those used for step-climb optimization in this study. Prior research has shown potential benefits from such joint optimization that meet or exceed projected benefits from independent speed and altitude modification [14].

The large sample size provided by the ETMS database allows for detailed examination of specific airlines, fleets, regions, and routes. An analysis of US domestic operations indicates that a large subset of flights operate far from the optimal speed and altitude. This remains true after accounting for certain system constraints, such as the necessity of using step climbs or LRC speed profiles to reduce flight time. In terms of altitude, 50.6% of domestic US flights could reduce cruise fuel consumption by 1% or more using optimal 2000-foot step climbs. In terms of speed, 37.0% of domestic flights could achieve the same savings by maintaining LRC speed throughout cruise.

Prior research in this area has shown that short stage lengths and regional jet aircraft tend to fly the least-efficient altitudes in today's system [14], while the least efficient speeds are more broadly distributed across different airlines and aircraft types [15]. It is reasonable to search for other causes for off-optimal operations and to explore operational methods to improve their performance.

The limited number of flights recorded in the IAGOS program prevents similar high-resolution examination, although there are clearly benefits from CASO in the long-haul realm in addition to domestic operations. Differences between the three airlines included in the sample study indicate that different operators approach flight planning and fuel management in different ways, inviting further investigation.

In order to analyze differences between operational domains and stakeholders, it will be important to expand the scope of the long haul analysis moving forward. This will allow differentiation between aircraft types, airlines, and CNS technology levels. Current plans include an extended CASO analysis using ANSP flight plan, amendment, and clearance records for a large segment of the North Atlantic Minimum Navigation Performance Specification (MNPS) airspace. This dataset will include all airlines and aircraft types currently using that airspace, allowing broader-based conclusions to be drawn about today's air transportation system efficiency.

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16. Abstract

This paper examines the potential fuel efficiency benefits of cruise altitude and speed optimization using historical fight path records. Results are presented for a subset of domestic US flights in 2012 as well as for long haul flights tracked by the European IAGOS atmospheric research program between 2010 and 2013. For a given lateral flight route, there exists an optimal combination of altitude and speed. Analysis of 217,000 flights in domestic US airspace has shown average potential savings of up to 1.96% for altitude optimization or 1.93% for speed optimization. International flights may be subject to different airline and/or air traffic management procedures and constraints. Examination of 3,478 long-haul flights, representing three airlines and a single aircraft type over a four-year period, indicates average potential savings of up to 0.87% for altitude optimization or 1.81% for speed optimization. This is equivalent to a mean fuel savings of 905 pounds and 1981 pounds per flight, respectively. Due to the limited sample set for long haul flight records, conclusions from this stage of the international study are limited to the specific airlines and aircraft types included in the IAGOS measurement program.

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