31st Congress of the International Council
of the Aeronautical Sciences

Belo Horizonte, Brazil; September 09-14, 2018

THE GLOBAL FUEL SAVING POTENTIAL OF INTERMEDIATE STOP OPERATIONS CONSIDERING METEOROLOGICAL AND OPERATIONAL INFLUENCES

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Keywords: *Intermediate Stop Operations, fuel efficiency, operational concept, meteorological influences, wind effect, optimized flight operations*

Abstract

Based on the current world-wide wide-body aircraft fleet a system-wide analysis of the fuel savings achievable through Intermediate Stop Operations (ISO) is conducted taking into account operational influences, including meteorological effects and flight planning policies. An analysis workflow is applied comprising of databases for aircraft movements, meteorology, and navigational information as well as models for trajectory calculation and optimization based on advanced aircraft performance models. The effect of wind is accounted for by the application of a newly developed statistical wind distribution method. For the first time, it is demonstrated, to what extent wind influences the suitability of airports serving as potential refueling stations, and how much fuel could be globally saved by ISO with today's wide-body aircraft conditions under more realistic assumptions.

1 Introduction

The increase of fuel efficiency in global aviation is of perseverative relevance both for economic and ecological reasons. Engineers are looking for even the smallest levers to reduce fuel consumption and in each new aircraft development program small savings are achieved through the use of new technologies. But also operational measures, like e.g. more efficient procedures due to changes in the ATM system as well as innovative fleet operation strategies are being discussed, which save fuel and eventually reduce emissions and operating costs during flight.

One of these solutions is the Intermediate Stop Operations (ISO) concept, which is based on the idea to reduce the stage length of flights by performing one or more intermediate landings during a mission. Due to shorter flight distances the amount of fuel burnt over the mission can be reduced, as the amount of fuel necessary to transport a certain percentage of the fuel for a long distance can be omitted. The payload-range efficiency (PRE) relating payload mass to the product of range and fuel mass therefore is highest on mission lengths between 4000 km and 6000 km using long-haul aircraft. A further increase of the PRE can be achieved by utilizing aircraft that are designed for shorter ranges, as the omitted fuel allows for a reduction of the aircraft's structural weight leading to benefits from snowballing effects.

1.1 Previous research

Numerous studies have been addressing the ISO concept differing in the approach to quantify the potential of the concept: Besides analytical methods for estimating weight proportions of aircraft designed for shorter ranges based on the Breguet formula, also conceptual aircraft design methods and design tools of higher fidelity are applied. The spectrum ranges from a generic single mission analysis to fleet and global level analyzes, assuming both ideally located stopover airports and real geographical airport distributions as well as real route networks. In addition to the fuel savings achievable by the concept previous studies also looked into the implications on flight times, operating costs, lifecycle costs, environmental impact and safety.

In the early studies by Green [1] and Nangia [2] a fuel saving potential of up to 51% for ISO with two stopovers was determined for long-haul aircraft redesigned for shorter ranges based on idealized assumptions on a mission level. Applying seating density corrections to the conceptual design relationships, Poll [3] and Hahn [4] adjusted these values downwards to 28%–29%. For ISO with only one stopover some studies (e.g. [5], [6], [7], [8]) present potential savings between 13% and 23% depending on the design range of the aircraft.

The potential savings from ISO with existing aircraft for one stopover were quantified by Creemers and Slingerland [8], Langhans et al. [7], Poll [3], Lammering et al. [6], Linke et al. [9] as well as Hartjes and Bol [10] and range between 5% and 15% depending on the used aircraft types. In particular, Poll stressed that the gain achieved by an additional stopover is relatively small (about 1.8% for existing aircraft, about 5% for redesigned aircraft) and thus an additional economic benefit compared to single-stopover ISO cannot be expected given the number of operational aspects to be considered.

The achievable fuel savings of ISO on fleet level as well as on global level were quantified by Green [11], Langhans et al., Linke et al. [12] and Poll. While Green estimates a potential of approximately 10% globally for ISO with aircraft optimized for shorter ranges, Langhans et al. and Linke et al. found 10%–11% as maximum possible savings in detailed studies, taking into account a real geographical airport distribution for flights operated by Boeing 777 or Airbus A330. Poll gives estimates for globally achievable savings in the range between 1% and 7%.

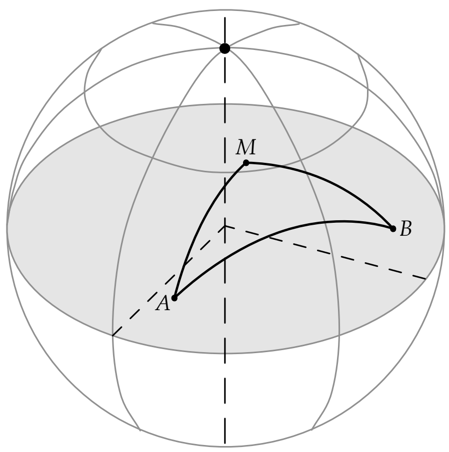

Fig. 1 For the definition of detour and offset factor of an intermediate airport (based on [13])

1.2 Problem description

So far, in the studies that performed system-wide analyzes of the concept's implications flight operations were modeled in a simplified way neglecting any meteorological effects, like e.g. wind and temperature, as well as any flight planning procedures normally used by airline dispatchers to optimize flight routes and profiles. Moreover, the aircraft performance models used for these investigations result from conceptual aircraft design methods that partially were calibrated with published data on a mass break-down level and therefore lack the required level of accuracy for more realistic operational computations. A more recent study by Hartjes and Bol [10] considers the wind impact by assuming constant headwind or tailwind speeds and airline-preferred vertical flight profiles, but only looks on three selected flight routes.

This paper presents a system-wide analysis of the fuel saving potential of Intermediate Stop Operations with the current world-wide aircraft fleet in a real flight and airport network. For the first time, all aircraft types that potentially benefit from ISO are considered and realistic operational influences are taken into account. In particular, these influences include a.) the effect of wind on the selection of refueling airports, stage lengths and fuel savings; b.) the flight planning policy of the aircraft operator assuming wind-optimal routing, long-range cruise and optimum stepped climbs. Flight operations are modeled more precisely through the application of the most accurate BADA (Base of Aircraft Data) aircraft performance models (model family 4) provided by EUROCONTROL.

2 Methodology

An analysis workflow was used that is capable of determining the fuel consumption for a given large-scale traffic scenario of ISO and reference missions. Each ISO mission consists of two flight segments connecting the origin to the destination airport via a stopover at the refueling airport, whereas the corresponding reference mission is represented by the one-stage direct flight segment from origin to destination airport (O-D pair). It is assumed that the ISO mission is performed by the same aircraft type as used for the direct flight ("self-substitution").

Mission data was taken from Sabre's Market Intelligence flight schedule database for the first quarter of 2010 and flight frequencies were scaled up to the period of one year. As previous studies have revealed that only wide-body aircraft actually show a fuel saving potential in self-substitution on mission lengths

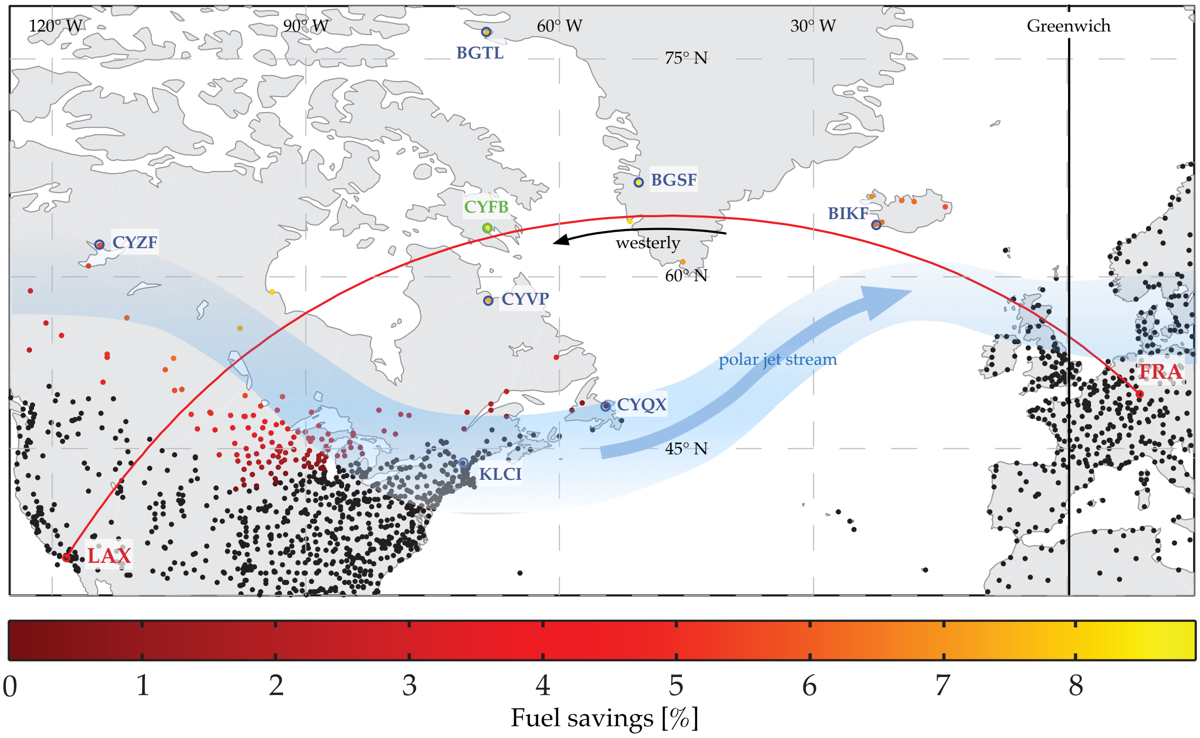

Fig. 2 Location and fuel saving potential of candidate refueling airports for flights from FRA to LAX with a Boeing 747-400 in the presence of headwind

above 2500 NM, the study is limited to the global wide-body aircraft fleet. Region-dependent passenger load factors were calculated based on IATA economics statistics.

The mission fuel is determined using a database of pre-calculated "reduced" flight profiles. These profiles were computed for all wide-body aircraft using DLR's Trajectory Calculation Module (TCM) (see [14]), for a parameter variation of segment distance and load factor. Applying BADA 4 aircraft performance models with an integrated profile optimizer the missions were simulated by TCM, which models the aircraft motion by using a Total Energy Model, resulting in optimal altitude profiles including step climbs depending on the selected step climb strategy and the heading-dependent available flight levels. As cruise speed the long-range cruise Mach number was assumed.

Navigational airport data, including the geographical coordinates were obtained from the European Aeronautical Information Service Database (EAD).

Both wind-optimal and great-circle (orthodromic) flight planning strategies are considered. For the determination of wind-optimal flight routes an optimal control approach is applied solving the so-called Zermelo problem [14]. Based on a given origin-destination pair the optimizer seeks for the minimum-time track by finding the optimal progression of the aircraft's heading (control variable) such that the overall flight time (cost functional) is minimized while satisfying certain contraints characterized by the equations of motion. This optimal control problem is solved by translating it into a boundary value problem and solving the corresponding system of differential equations.

A new efficient method presented by Swaid [15] and Linke [16] was used to account for the average effect of wind. Meteorological data was taken from the European Centre for Medium-Range Weather Forecast (ECMWF) for a grid of $.75° \times .75°$ with global coverage for the period of one year (2012) and in a post-process the occurring wind situations were statistically analyzed resulting in a database of local wind distributions. Based on these data characteristic mean equivalent still air distances, i.e. the actual distance flown taking into account wind, for any given flight route are determined 100 times faster than evaluating daily meteorologies separately without no significant loss in accuracy. Hence, this method is particularly well suited for system-wide analyzes of longer peri-

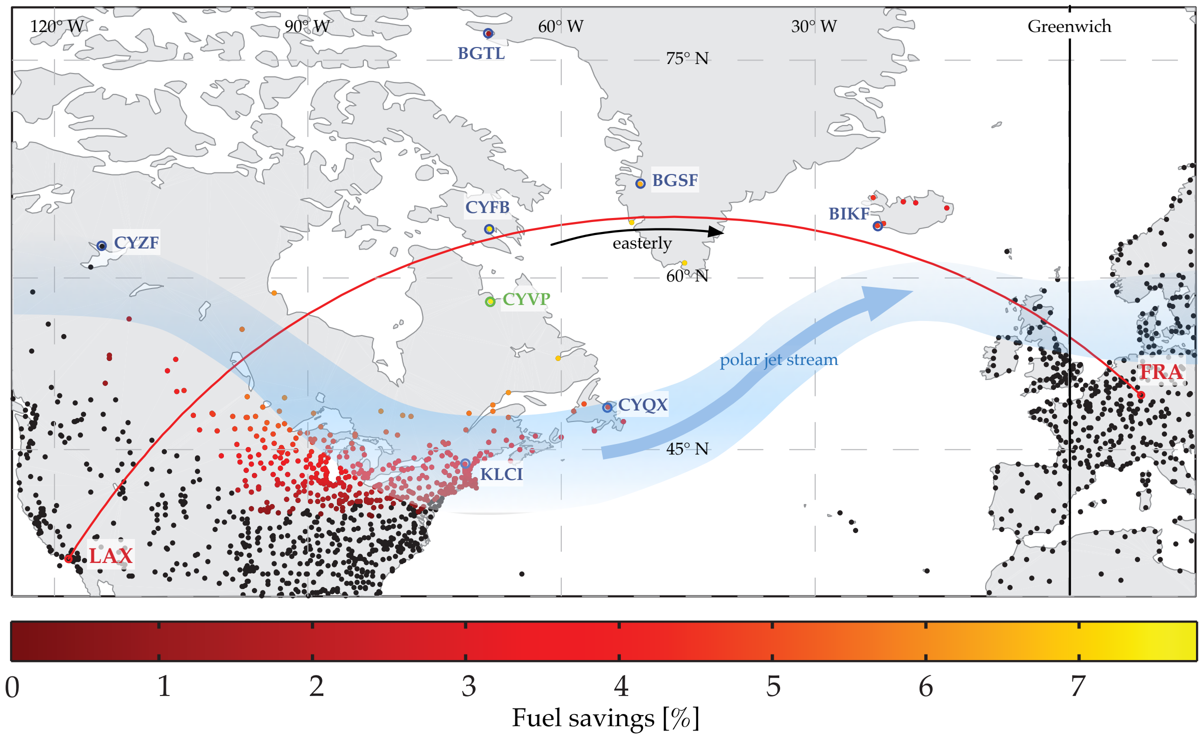

Fig. 3 Location and fuel saving potential of candidate refueling airports for flights from LAX to FRA with a Boeing 747-400 in the presence of tailwind

ods of time (e.g. one year) without neglecting cross-wind effects as opposed to other methods. The use of climatological wind fields instead would have lead to errors as extreme wind situations are averaged out.

3 Application and results

The fuel saving potential of ISO strongly depends on the availability and location of adequate refueling airports. There are flight connections no airport can be found for that actually leads to fuel savings if used for a refueling stopover. In these cases a direct flight is the best operating mode for the airline. However, for the majority of flights due to a high density of suitable airports several options for an intermediate stop exist. In these cases, it is assumed that the airlines chooses that airport, which minimizes the mission fuel consumption.

According to [13] the location of an airport for an intermediate landing with respect to the original flight mission can be described using two parameters:

$$f_{\text{detour}} = \frac{\overline{AM} + \overline{MB}}{\overline{AB}} \quad (1)$$

$$f_{\text{offset}} = \frac{\max(\overline{AM}, \overline{MB})}{\overline{AM} + \overline{MB}} \quad (2)$$

While the detour factor f_{detour} describes the ratio of the extended mission length due to the intermediate stop with respect to the direct mission distance, the offset factor f_{offset} characterizes the excentricity of the intermediate stop airport's location from the theoretically optimal location in the middle between the departure and destination airports. It is noted that air distance values are used whenever wind is considered. As a consequence, there are constellations, where $f_{\text{detour}} < 1$, indicating that the ISO mission is shorter than the reference due to a beneficial tailwind situation.

3.1 Influence of wind on airport suitability

We analyzed the effect of wind on the suitability of airports serving as potential refueling locations for ISO. Based on the compiled traffic scenario and the airport database for each mission we identified that airport that leads to maximum fuel savings if used for a stopover. First, all potential candidate airports have been pre-selected by filtering for airports equipped with at least an asphalt-surfaced runway and an Instrument Landing System. The search space was further reduced by limiting the detour to $f_{\text{detour}_{\max}} = 1.2$ and the offset to $f_{\text{offset}_{\max}} = 0.8$. The remaining air-

Table 1 Comparison of fuel saving potentials of selected airports for flights between Frankfurt and Los Angeles

ICAO	Airport	no wind	wind	
			westerly	easterly
BGSF	Kangerlussuaq, Greenland	7.34%	8.63%	6.47%
BGTL	Thule Air Base, Pituffik, Greenland	4.12%	7.53%	1.17%
BIKF	Keflavik International, Reykjavik, Iceland	5.34%	6.33%	4.67%
CYFB	Iqaluit, Nunavut, Canada	**7.90%**	**8.88%**	7.30%
CYQX	Gander International, Newfoundland, Canada	2.49%	0.08%	4.65%
CYVP	Kuujjuaq, Quebec, Canada	7.42%	7.29%	**7.77%**
CYZF	Yellowknife, Northwest Territories, Canada	2.32%	5.57%	-
KLCI	Laconia, New Hampshire, USA	-	-	3.09%

ports were used to construct candidate ISO missions, which were then analyzed with respect to the fuel consumption by an exhaustive search algorithm assuming great circle routes. This analysis was done for a windless scenario and repeated applying the above mentioned technique to process annual mean air distances to consider wind.

In order to better understand and discuss the influence wind has on the suitability of a particular airport to serve as refueling location, we phenomenologically analyze the effect in the following based on a representative long-haul mission between *Frankfurt* (FRA) and *Los Angeles* (LAX).

Figure 2 shows the resulting candidate airports serving as refueling station during flights from FRA to LAX colored (dark red to yellow) according to their respective fuel savings relative to the direct flight. The missions have been simulated using a Boeing 747-400 with a typical seat load factor of 77%. A selection of airports marked by blue circles is highlighted for a more detailed numerical comparison in table 1. The most suitable airport is marked by a green circle. For the flight FRA-LAX, which is generally subject to a strong headwind caused by the polar jet stream, the airport of *Iqaluit* (CYFB) is best suited with a potential of nearly 8.9%.

In contrast to that, in figure 3 the opposite flight direction (LAX-FRA) is depicted in the same way. Here, the jet stream provides a tail wind component on average making the airport of *Kuujjuaq* (CYVP) with a fuel saving potential of 7.8% the best option for a refueling stop. In the direct comparison shown in table 1 also the values for a no-wind case are shown. It can be seen that in the presence of wind airports north of the great circle (red line) provide an increased fuel saving potential on the westerly flight. *Thule Air Base* in the northern part of Greenland shows a potential of 7.5% while on the easterly flight its potential is nearly negligible (1.2%). However, for the flight LAX-FRA the high-potential area moves towards south suddenly enabling a large number of US-american airports (e.g. *Laconia*, KLCI) to serve as beneficial refueling stations.

In summary, it can be noticed that in the presence of wind the locations of best-suited airports for an intermediate stop on long-haul missions may vary significantly depending on the flight direction. Previous studies, like e.g. [7], which analyzed the additional landings and take-offs caused by the ISO concept at a certain intermediate airport, hence, overestimated the number of additional flight movements by neglecting the wind effect and thus assuming symmetry between both flight directions.

We performed this analysis for the entire traffic scenario of the global wide-body aircraft fleet for the period of one year, in order to determine to what extent the consideration of wind changes the global distribution of optimally located refueling airports. The results are shown in figure 4. The map shows the 20 most ISO-affected airports both for a no-wind scenario and a scenario considering wind. It can be observed that wind changes the number of additional flights a particular airport has to process. Obviously, some airports (black colored) both exist in the top 20 of the no-wind scenario and the wind scenario, others either appear in the no-wind or in the wind scenario. We found, that 85.8% missions from the scenario can be efficiently operated in ISO mode with fuel savings. 440 different airports were found to be globally optimally-located for at least one ISO mis-

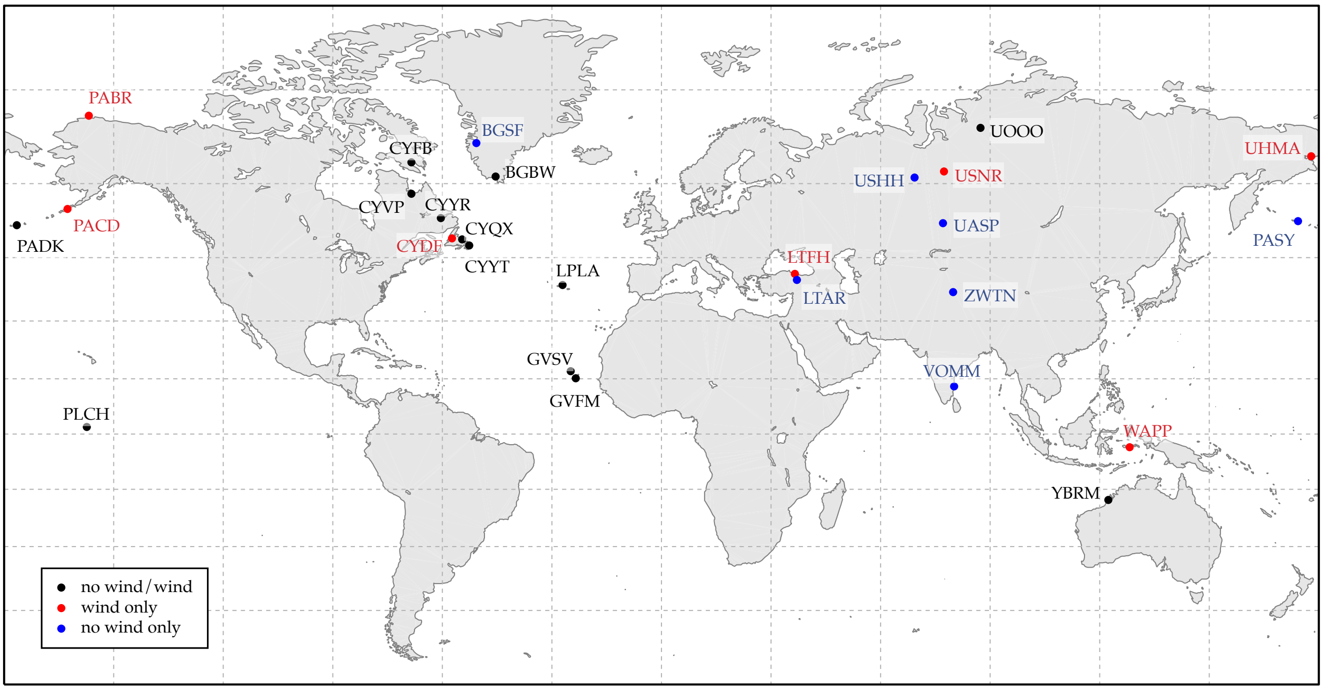

Fig. 4 Geographical distribution of the 20 most affected airports due to ISO with and without wind (black dots depict airports that are both among the top 20 airports in still air and in the presence of wind; blue dots represent airports that only rank among the top 20 if wind is neglected; red dots show airports that are only top-ranked if wind is considered.)

Table 2 Comparison of the top 20 most affected ISO airports in the presence of wind sorted by number of additional flight movements (percentages indicate the proportion of the totality of all ISO missions/flights/fuel savings)

rank	ICAO	location	# missions		# flights		fuel savings	
1	CYQX	Gander, Newfoundland, Canada	185	5.04%	**56 090**	**6.31%**	54 732 t	1.75%
2	CYYT	St. John's, Newfoundland, Canada	**233**	**6.35%**	46 387	5.22%	69 619 t	2.23%
3	LPLA	Lajes, Azores, Portugal	166	4.53%	27 680	3.12%	42 652 t	1.37%
4	CYYR	Goose Bay, Labrador, Canada	86	2.35%	26 432	2.97%	53 303 t	1.71%
5	BGBW	Narsarsuaq, Greenland	88	2.40%	23 685	2.67%	42 031 t	1.35%
6	PADK	Adak (Island), Alaska, USA	56	1.53%	19 239	2.17%	87 004 t	2.79%
7	YBRM	Broome, Western Australia, Australia	40	1.09%	14 586	1.64%	24 443 t	0.78%
8	CYFB	Iqaluit, Nunavut, Canada	38	1.04%	12 401	1.40%	71 662 t	2.30%
9	GVSV	São Vicente, Capeverde	43	1.17%	11 878	1.34%	50 885 t	1.63%
10	CYVP	Kuujjuaq, Québec, Canada	31	0.85%	11 856	1.33%	53 563 t	1.72%
11	LTFH	Samsun, Turkey	29	0.79%	11 644	1.31%	9 072 t	0.29%
12	PLCH	Banana, Kiritimati (Island), Kiribati	36	0.98%	10 959	1.23%	**123 900 t**	**3.97%**
13	WAPP	Ambon, Indonesia	38	1.04%	10 946	1.23%	18 942 t	0.61%
14	GVFM	Praia, Santiago (Island), Capeverde	46	1.25%	10 923	1.23%	45 310 t	1.45%
15	USNR	Raduzhny, Russia	40	1.09%	9 950	1.12%	41 152 t	1.32%
16	CYDF	Deer Lake, Newfoundland, Canada	34	0.93%	9 604	1.08%	20 257 t	0.65%
17	PABR	Barrow, Alaska, USA	26	0.71%	8 874	1.00%	87 402 t	2.80%
18	PACD	Cold Bay, Alaska, USA	20	0.55%	8 797	0.99%	62 746 t	2.01%
19	UHMA	Anadyr, Russia	28	0.76%	8 658	0.97%	85 411 t	2.74%
20	UOOO	Norilsk, Russia	28	0.76%	7 495	0.84%	55 397 t	1.78%
			1 291	35.21%	348 086	39.17%	1 099 484 t	35.24%

Table 3 Share of Gander and St. John's in the most affected ISO airports in a no-wind scenario; complete table can be found in [16]

rank	ICAO	# missions		# flights		fuel savings	
1	CYQX	**226**	**6.31%**	**73 387**	**8.40%**	47 721 t	1.69%
2	CYYT	212	5.92%	38 901	4.45%	65 143 t	2.31%

sion, 33.3% more than in the corresponding no-wind case. This finding is consistent with the higher diversification of possible ISO airports due to wind shown in figure 4.

Moreover, table 2 lists the details of the 20 most affected ISO airports if wind is considered. In terms of additional landings and take-offs caused by ISO the airport of *Gander* (CYQX) is the most relevant airport. This is also the case for the no-wind scenario, as can be seen in table 3; however, wind reduces the number of additional flight movements from 73 387 by approximately 24% to 56 090. Instead, more flights are routed via *St. John's* (CYYT), which ranks second and is highest in terms of missions in the wind scenario. This observation is consistent with the above shown results: On trans-Atlantic routes easterly flights are canalized into the jet stream making St. John's more favorable for an intermediate stop than Gander.

Other relevant airports are *Lajes* (LPLA) on the *Azores Islands* and the *Cape Verde Islands* for trans-Atlantic flights as well as airports on the Aleutian Islands (Alaska) and in Siberia, which serve as refueling stations for trans-Pacific flights. Also airports in northern Turkey, in Indonesia, Northwest Australia, and along a vertical band over middle Asia are of importance and contribute to the fuel saving potential of ISO. Interestingly, *Cassidy International* airport (PLCH) in Kiribati amidst the Pacific Ocean serves as optimal ISO airport for 36 missions leading to the highest overall fuel savings (123 900 tons) accounting for nearly 4% of the global fuel savings that can be realized by ISO. The reason for this is, that the corresponding flights between the US West Coast and Eastern Australia are particularly long and the airport density in the Pacific area is low. The longer a mission is the more fuel can be saved by a refueling stop.

From all ISO missions the maximum single-mission savings (14.95%) can be achieved on flights from *Los Angeles* to *Singapur* with a stopover in *Sokol*, Russia (UHMM). Globally, on all ISO missions 4.39% of fuel can be saved on average.

3.2 Airport suitability with wind-optimal flight planning

Today, aircraft operators often plan their flights such that the air distance becomes as short as possible taking the wind situation during flight into account. In the following it is analyzed which impact such a wind-optimal flight planning would have on the properties of the available candidate refueling airports of a mission using the example of a flight from *Havana* (HAV) to *Madrid* (MAD) with an Airbus A340-600 aircraft (seat load factor 77%) on May 3, 2012. A static wind field at 1200 UTC was applied and the wind-optimal flight routes were computed using the optimal control algorithm described in section 2 assuming a constant pressure altitude of 37 000 ft and Mach number of .83. Figure 5 shows the resulting wind-optimal flight tracks for six possible ISO missions with the actual wind situation plotted in the background. Based on this, the wind-optimal direct route (black solid line) proceeds over the Azores Islands south of the great circle connection. This causes the airport Lajes Field (LPLA) to be the optimal airport for a refueling stop, as it provides the smallest detour factor.

Table 4 lists all properties of the relevant airports. Obviously, the two relevant airports in Newfoundland, Gander (CYYT) and *St. Pierre* (LFVP), are not attractive in this particular wind situation as intermediate stops would lead to a significant increase in fuel burn compared to the direct flight. The airport of *Bermuda* (TXKF) turns out to be best suited for a no-wind situation, but only is the third-best option for performing a refueling stop if the meteorology of the selected day is accounted for. Table 4 also includes mission details for a orthodromic route planning in the presence of wind. It can be observed, that wind-optimal flight planning reduces the possible fuel savings that can be achieved by the ISO concept. This effect can be explained with the possibility to shorten the direct flight route by in this case 91.5 NM compared to the great circle making the reference flight already more fuel efficient.

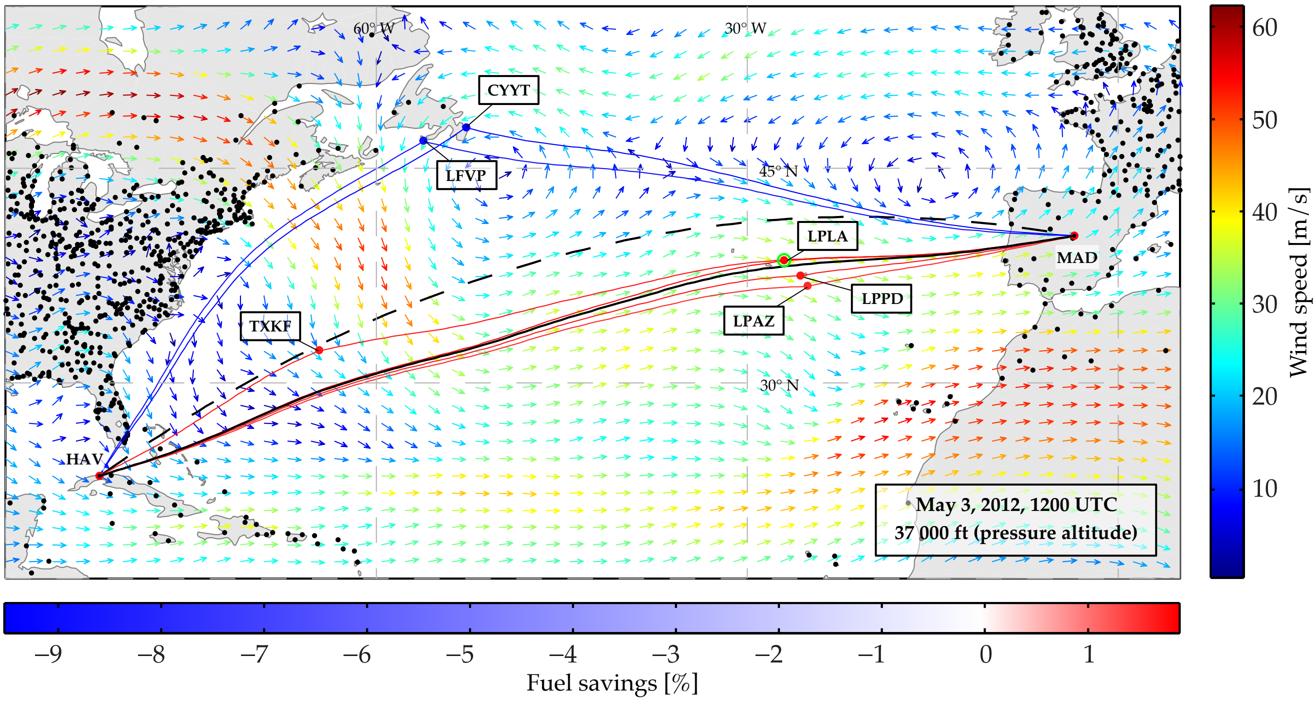

Fig. 5 Wind-optimal routes and fuel saving potentials for ISO missions from HAV to MAD operated by Airbus A340-600 on 3 May, 2012, 1200 UTC (black solid line: wind-optimal direct flight; dashed line: great circle)

Table 4 Properties of refueling airports on flight connection HAV–MAD for wind-optimal and orthodromic routes (meteorology: May 3, 2012)

airport	air distance	detour factor	offset factor	fuel savings
wind-optimal ISO mission planning				
Direct	3742.41 NM			
CYYT	2125.31 NM + 2118.47 NM	13.40%	0.5008	-9.53%
LFVP	1971.01 NM + 2248.49 NM	12.75%	0.5329	-8.93%
LPAZ	2824.24 NM + 924.26 NM	0.16%	0.7534	1.51%
LPLA	2760.25 NM + 982.49 NM	0.01%	0.7375	**1.89%**
LPPD	2808.70 NM + 934.99 NM	0.03%	0.7502	1.69%
TXKF	1080.77 NM + 2682.27 NM	0.55%	0.7128	1.67%
orthodromic (great circle) ISO missions				
Direct	3833.95 NM			
CYYT	2135.27 NM + 2177.82 NM	12.50%	0.5049	-6.63%
LFVP	1982.16 NM + 2319.94 NM	12.21%	0.5393	-6.05%
LPAZ	2841.75 NM + 928.34 NM	-1.67%	0.7538	4.11%
LPLA	2783.66 NM + 991.92 NM	-1.52%	0.7373	**4.48%**
LPPD	2828.39 NM + 941.02 NM	-1.68%	0.7504	4.28%
TXKF	1081.82 NM + 2743.49 NM	-0.23%	0.7172	4.27%

In reality, aircraft operators would select a refueling airport not solely based on its fuel saving potential, but also based on further criteria, including e.g. (i) the existence of alternate airports in the vicinity in case a diversion is required; (ii) the availability of sufficient capacity, infrastructure and fuel supply to efficiently service the aircraft; and (iii) local fuel prices as well as navigational and landing fees.

4 Summary and Conclusions

A system-wide analysis of the fuel savings achievable through Intermediate Stop Operations with the current world-wide wide-body aircraft fleet in a real flight and airport network is presented. For the first time meteorological effects and flight planning policies are taken into account in the analysis of fuel savings.

Results demonstrate that in the presence of wind the locations of best-suited airports for an intermediate stop on long-haul missions may vary significantly depending on the flight direction. Previous studies, like e.g. [7], which analyzed the additional landings and take-offs caused by the ISO concept at a certain intermediate airport, hence, overestimated the number of additional flight movements by neglecting the wind effect and assuming symmetry.

Moreover, wind-optimal flight planning with up-to-date wind information influences the suitability and the potential savings of a possible intermediate airport. For example, depending on the route and location of the airports, some ISO missions may experience potential reductions, while at the same time allowing additional airports to be considered.

The findings obtained from this single mission analysis lead to the conclusion that the concept's global fuel saving potential is actually reduced, if aircraft operators plan their flights in a wind-optimal way based on up-to-date wind data, as it reduces air distances for direct flight connections.

However, even with the current aircraft in self-substitution significant fuel savings can be achieved by ISO, up to 15% depending on the mission length, making the concept an interesting alternative for sustainable and resource conserving operations promising also economic benefits for airlines, yet not very comfortable for the passenger.

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Acknowledgments

The author appreciates the contributions by Majed Swaid and Benjamin Lührs who were involved in the development of the assessment workflow and contributed with their valuable knowledge on trajectory calculation and wind modeling. Moreover, the author would like to thank EUROCONTROL for the provision of BADA version 4 aircraft performance models.

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