IN-FLIGHT REFUELING FOR COMMERCIAL AIRLINERS

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1 Introduction

Current long distance commercial flights require refueling stops, which always lead to an increase in total travel time. Flying with ultra long range aircraft can make refueling stops redundant, but at the expense of replacing useful payload capacity with fuel in order to cover the long distance. In other words, fuel is burned to transport fuel. Furthermore, the rising fuel price and increasing attention to the aviation industry's role in global climate change, place pressure on commercial aviation to improve fuel efficiency. Therefore refueling during the flight can be the ideal option to save time, increase payload, and improve fuel efficiency.

In-flight refueling (IFR) has been used successfully in the military for the past 85 years. However, it has not yet been applied in commercial aviation. The existing refueling systems and operational experiences gained from the military provide the initial steps for implementation in commercial aviation.
The project includes the designs of the refueling system and investigations on performance, economical and environmental aspects to demonstrate the attractiveness of IFR, as defined in the project objective statement:

Design an in-flight refueling system for commercial aviation and evaluate its economic and environmental potential and safety, within 10 weeks with 10 people.

2 Mission need statement and requirements

The mission need statement, which mainly focuses on the design, is defined as:

Refuel a commercial airliner as close to cruise speed and cruise altitude as possible and thereby increase its performance and economic viability for long range flights.

The project has to comply with many requirements to achieve this mission. The requirements are specified in three different categories:

Technical requirements:

- The IFR system must be possible to be implemented in the current Air Traffic Control system
- Refueling must be possible close to cruise conditions at all times of the day (Mach 0.5 – 0.8 and at Flight Level 300) at a transfer rate of 4500 L/min

Safety requirements:

- IFR must be at least as safe as landing and take-off combined

Economical requirements:

- An IFR mission must be more:
- profitable when compared to a non-stop flight
- fuel efficient than a non-stop flight
- time efficient than an intermediate stop flight

Next to the requirements, the project is also confined within constraints. The current aviation regulations and environmental impact of IFR have to be taken into consideration during the design.

3 Conceptual and final designs

The design for an IFR system contains three major parts: the Fuel Transfer System (FTS), control systems and operational systems. For each part, various straw man concepts were developed after which the trade-offs were performed based on different criteria. After that, the winner concept was investigated in detail and possible improvements were included.

Fuel Transfer System

Figure 10.1 shows the two remaining FTS concepts after discarding the obvious non-feasible concepts. The boom-receptacle system transfers fuel using a rigid boom, which can be steered and inserted into the receptacle on top of the receiver by a boom operator. For the probe-drogue system, the receiver must insert its probe into the drogue located at the end of the hose, by maneuvering the entire receiving aircraft in order to receive fuel.

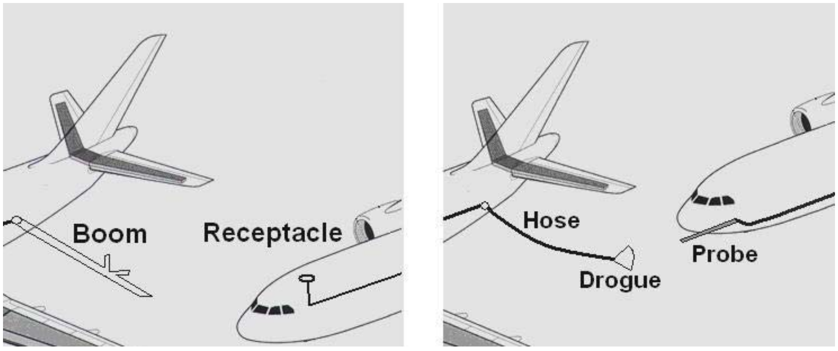

Figure 1: Boom-receptacle system (left) and probe-drogue system (right)

Both concepts scored nearly equal on most criteria, but based on the controllability, required fuel flow rate and safety, the boom system was chosen as the winner concept. The limited extendibility of the boom makes it less agile when refueling a commercial airliner. Another limitation is accessibility during maintenance. These weaknesses are further investigated and improved in the final design phase.

Control system

The control system mainly contains instrumental devices that provide controllability and aim to maintain relative position and speed during the refueling operation. Two types of control systems are considered: manual and automatic control, using instrumental cues and electronic sensors respectively. After the trade-off, it is determined to combine both control manners for increased reliability and safety. During the final design, both manual and automatic controls are implemented with additional aids, varying from visual aids to digital automatic sensors in order to increase reliability and safety.

Operational system

The operational system incorporates the methods how refueling operations should be performed in terms of logistics and planning. The developed concepts show that the refueling could be done either in reserved regions or along the flight path of the receiver. The trade-off criteria such as fuel efficiency, time efficiency and safety are paramount to determine the winner concept: along path refueling. The winner concept is further elaborated during the final design phase. Figure 2 shows the final operational concept which includes a redundant refueling region and holding areas (ellipses) in order to cope with uncertainties like bad weather and availability of the refueling regions. Planning is considered as the most crucial and complex part of the refueling operation since any improper planning will lead to unfavorable delays: every second of delay will generate an additional 40 seconds of approach time. Delays however can be accounted for by modifying the holding pattern before entering the refueling region.

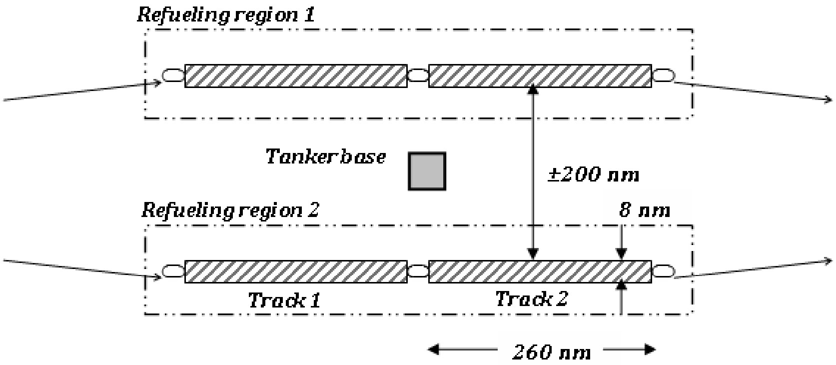

Figure 2: Refueling regions

4 Performance analysis

In order to evaluate the performance of an IFR flight compared to non-stop flights and intermediate-stop flights, a computer model was made in which the payload-range efficiency (PRE) was calculated for three cases (Los Angeles-Amsterdam, Sydney-Los Angeles and Amsterdam-Sydney). PRE is expressed in terms of payload (PL), range (R) and fuel used (WF).

$$PRE = \frac{R \cdot PL}{W_F}$$

The formula is applied to all cases to find the optimum location for refueling. Also the ideal aircraft type for each route and mission type is found for comparison purposes.

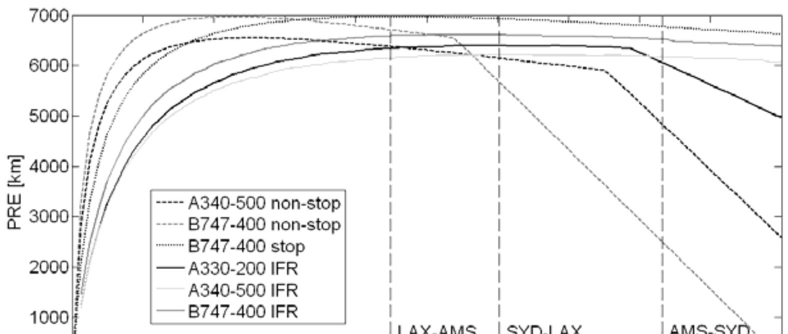

Figure 3: PRE diagram for various ranges

Figure 3 shows that on flights further than 6,000 km it becomes interesting to look at the alternatives to non-stop flight. The intermediate stop is always the most fuel efficient, but is less time efficient than IFR. Therefore an assessment must be made to investigate which is more interesting, fuel efficiency or time efficiency. The outcome of this assessment is that it depends on various aspects like fuel price and market demand for flight time savings.

5 Economical and environmental evaluation

Next to technical feasibility, the attractiveness of IFR also depends on its economical feasibility and the environmental impacts it will cause. Therefore several analyses were performed to evaluate IFR on both aspects.

Economical evaluation
The economical evaluation consists of financial analyses regarding costs, revenue and profit for all cases. For illustration, the Amsterdam-Sydney route (AMS-SYD) is presented here.

The major direct operating costs of an airline are the fuel costs, maintenance costs, crew costs, landing fees and en-route charges. Performing IFR allows the airlines to replace the landing fees at the intermediate airport by the tanker costs. After evaluating different non-stop and intermediate-stop flights based on the costs analyses and the revenue estimations, it follows that it is more profitable to aerially refuel a medium range aircraft compared to a long range aircraft. Table 10.1 shows the investigated profit analysis for the AMS-SYD route; it is normalized with respect to the non-stop flight to demonstrate the differences between various types of flight. For each mission the most efficient aircraft type was chosen. Compared to the non-stop flight, IFR is more profitable. But the flight with an intermediate stop is even more interesting in this case.

Quantity (index)	A340-500 non-stop	B747-400 intermediate stop	A330-200 IFR
Operational cost	1	1.13	1.17
Revenue	1	1.85	1.12
Profit	1	2.51	1.06
Profit per passenger	1	1.61	1.03

Table 1: Profit analysis for AMS-SYD route

Environmental evaluation
The environmental impact of IFR was evaluated for all cases and only the AMS-SYD route is discussed here. For evaluation, aircraft emissions and noise of different types of operations are determined. Carbon dioxide (CO2) is regarded as the benchmark to measure aircraft emissions and only the noise levels during take-off and landing are considered. Table 10.2 presents that the IFR flight is more environmentally friendly compared to non-stop flight since less CO2 per kilogram payload is emitted. It is however less efficient than intermediate stop flight since the flight with intermediate stop can carry more payload. The results of the noise evaluation show that the noise impact at the intermediate airport will disappear when performing IFR since the stop is omitted.

Quantity	A340-500 non-stop	B744-400 intermediate stop	A330-200 IFR
Payload [t]	43.2	67.2	44.7
Fuel total [t]	148.9	168.4	123.0
CO2 emitted [t]	473.5	536.4	391.9
CO2/payload [kg/kg]	11.0	8.0	8.8

Table 2: CO2 emissions of AMS-SYD route

Furthermore, performing IFR contributes to time saving and increases fleet flexibility, but the added value of these advantages is very difficult to measure quantitatively. In addition, the willingness of the passenger to pay more for the time saved still requires further investigation.

10.6 Operational concerns

In-flight refueling must not only be technically and economically feasible, there are also some operational concerns. First, the current crew regulations prohibit executing flights longer than 14 hours according to European air law. However, the AMS-SYD flight takes about 20 hours including preparation and debriefing. To make this possible, the duty time must be increased. In that case, the flight will be executed by two crews and they switch during flight. After landing, two new crews fly the aircraft back to Amsterdam.

Another concern is the tanker base location. One should consider geographical concerns such as domestic regulations, political issues, population and economics. For example, the AMS-SYD flight is not advised to refuel above or install a tanker base in Myanmar for political reasons or to fly over the Himalayas for safety reasons.

For refueling operations, there are two refueling tracks after each other to cope with peak demands. Also, holding patterns are located in front of the track to account for delays as shown in figure 2. There is another region of two tracks situated at the other side of the base to account for bad weather. Efficient planning is done by designating multiple slots of 10 minutes which airlines can buy.

7 Conclusion and recommendations

Conclusion

IFR enables an airliner to perform a very long-haul flight without making an intermediate stop. IFR is technically feasible using the conventional boom system which is a proven technology in the military where large aircraft like the AWACS and the C-5 Galaxy can be in-flight refueled.

The results of the economical evaluation show that a non-stop flight executed by an ultra long range aircraft is less fuel efficient than an in-flight refueled medium range aircraft on the same route. Furthermore the lifetime of the aircraft is increased when performing IFR since the number of take-off and landing cycles is reduced, which results in lower maintenance costs. Because of the increase in fuel efficiency, IFR flights are more profitable than non-stop flights. However, IFR flights are less fuel efficient than intermediate stop flights. Nevertheless, market research shows that the demand for flying non-stop is still high.

Also, IFR is more environmentally friendly than non-stop flight since the emissions per kilogram payload are lower. It is also interesting to notice that in case of IFR, environmental and economical benefits go hand in hand and the environmental benefits are even larger than the economical advantages.

Recommendations

Considering the amount of time available, not every aspects of IFR is studied in detail, therefore it is recommended to perform further research on following subjects:

- Receiver modification for increased maximum zero fuel weight
- Receiver recertification
- Wind tunnel experiments regarding the aerodynamic effects of the boom and the interferences between two aircraft
- Flight envelope investigation of both aircraft concerning the maneuverability at high altitude
- Airline work regulations
- Passenger acceptance and comfort