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Aerial Refueling Implications for Commercial Aviation

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Numerical refueling missions were simulated with a 747-400 tanker for three different sized aircraft—a 747-400, a 777-300, and an A318—to examine the impact on payload capability. Simplified performance and economic models were used to optimize the payload improvement with respect to the refuel point. Optimum refuel points for maximum payload improvement resulted in 88, 110, and 111% payload carrying increases for the A318, 777, and 747 respectively. The mission distance location for the optimum refuel point was observed to increase with increasing aircraft weight. A return on investment of less than one year was predicted for the large aircraft, although the optimum economic refuel point did not coincide with the point for maximum payload increase. Additional benefits were identified to include increased revenue to both the manufacturers and the airline operators, in the form of more product options, more revenue flight hours, increased airframe life, and the possibility for improved takeoff performance and noise reduction. The implementation of in-flight refueling is also proposed to lead to second cycle benefits of a revolution in future commercial aircraft conception and design.

Nomenclature

M_{ff} = mission fuel fraction

Introduction

ONE, perhaps not so obvious, limitation of the present-day air transportation industry is the airplane itself. The performance of a commercial aircraft is hampered by the fact that flights today must carry the entire fuel load required for a mission on board the aircraft at takeoff. Consider a typical 747-400 mission. For a range of 7325 n miles, or 13,566 km, given an operating empty weight (OEW) of 394,000 lb (1,752,512 N) and a maximum payload of 97,500 lb (433,680 N), the aircraft must carry 383,810 lb (1,707,187 N) of fuel onboard at takeoff, almost the equivalent weight of the empty plane itself. If the concept of in-flight, or aerial, refueling were to be implemented in the commercial market, the future of aircraft transportation could be completely transformed. In addition to providing new incentives and potentials for aviation, there would be a revolutionary change in the way airplanes are designed to take advantage of this opportunity.

Aerial refueling is used extensively by the military[1] today, as illustrated with the KC-10A in Fig. 1, but an historical review indicates the concept of commercial air refueling was proposed as early as 1934 by Alan Cobham in Britain.‡ According to the website cited in the footnotes, the first patent for aerial refueling was granted in 1921 to Alexander P. de Seversky, an engineer in the U.S. War Department and former pilot in the Imperial Russian Navy. By the 1920s, aerial refueling was being pursued extensively by the U.S. Army, although it was not until the late 1940s that the new head of the Strategic Air Command, U.S. Air Force General Curtis LeMay, made aerial refueling a major priority. Over the past 50 years, technological advances have successfully led to the flying boom and the probe and drogue refueling systems, but these aerial refueling systems have remained exclusively in the military sector. The U.S. Centennial of Flight Commission provides a more detailed overview of the history of air to air refueling,‡ citing economic reasons for the lack of commercial aerial refueling today. Additional details on the history of refueling can be found in Refs. 2–4.

Many aircraft missions exist that could benefit from a commercial midair refueling capability. Payload increase and range extension are obvious ones. It is envisioned, by some, that air travel over the Pacific will be driven more towards a point-to-point travel philosophy, similar to what has occurred over the Atlantic. The new Boeing 7E7 is an example of this type of thinking with goals of 250 passengers on routes of 8300 n miles (15,400 km). Commercial aerial refueling would further extend this market. Other missions could include more specific goals, such as reducing takeoff weight to increase takeoff and climb-out performance while still maintaining the required range. A reduction in takeoff weight would also help noise issues associated with very large commercial aircraft and recent versions of proposed commercial supersonic transports such as the high-speed civil transport.[5]

A previous preliminary study presented the potential of such a commercial refueling concept.[6] Two likely scenarios, a range improvement and a payload increase, were examined. The study indicated that although the potential capabilities with range improvement are dramatic, the economic potential from a payload increase is much more lucrative. For this reason, the latter has been examined in more detail and is the focus of the present study.

Figure 2 illustrates a simplified schematic of this type of mission. The mission aircraft (MA) takes off with a reduced fuel load, offset by an increased payload to maintain the original maximum takeoff weight (MTOW), and flies for a part of the given mission. A tanker aircraft then refuels the MA with the rest of the required mission fuel. The MA, ideally fueled up at cruise altitude and speed, then flies the rest of the mission. The tanker returns to base, or possibly enters a loiter phase to prepare to fuel up another aircraft.

Although this represents an idealized scenario, the framework allows the investigation of the impact of increased payload and refuel requirements for simplified aircraft missions. The present study examines the effectiveness of refueling over a large range of aircraft sizes and missions. A simplified economic evaluation follows along with a discussion on additional issues to be considered.

Aircraft Configurations

Mission Aircraft

Three aircraft configurations were considered in this study: an A318, a 777-300, and a 747-400. These aircraft were selected to examine a wide variety of payload and range capabilities. The weights and volumes used for the evaluations are listed in Table 1 and represent typical values for maximum payload missions. Several

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‡Data available online at http://www.centennialofflight.gov/essay/Evolution of Technology/refueling/Tech22.htm [cited 12 Jan. 2004].

Fig. 1 Wide-body aircraft in-flight refueling (courtesy of The Boeing Company).

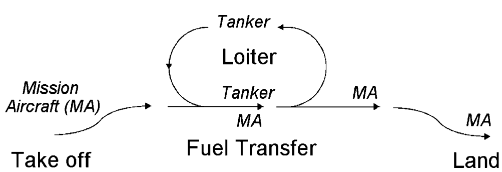

Fig. 2 Commercial aircraft refueling scenario.

Table 1 Mission aircraft parameters

Parameter	A318[a]	777-300ER[b]	747-400[c]
MTOW			
lb	145,600	660,000	875,000
N	647,629	2,668,800	3,892,000
OEW			
lb	84,600	351,700	394,000
N	376,301	1,564,361	1,752,512
MLW[d]			
lb	123,500	542,000	630,000
N	549,328	2,410,816	2,802,240
Fuel capacity			
lb	42,462	236,000	383,810
N	188,871	1,049,728	1,707,187
Payload			
lb	18,438	72,300	97,500
N	82,012	321,590	433,680
Range			
n miles	3,250	5,955	7,325
km	6,019	11,029	13,566
Est. fuel burn, cruise			
lb/h	13,000	19,000	30,000
N/h	57,824	84,512	133,440
Est. fuel burn, climb			
lb	6,000	20,000	26,000
N	26,288	88,960	115,648
Est. Time to Climb, h	0.25	0.45	0.4
Cruise Mach	0.78	0.84	0.855
Est. lift-to-drag ratio	17	18	16.4

[a]Data available online at http://www.airbus.com/product/a318_specifications.asp [cited 12 Jan. 2004] and http://www.airbus.com/product/a318_performance.asp [cited 12 Jan. 2004].
[b]Data available online at http://www.boeing.com/assocproducts/aircompat/acaps/777_23.pdf [cited 12 Jan. 2004].
[c]Data available online at http://www.boeing.com/assocproducts/aircompat/acaps/747_4.pdf [cited 12 Jan. 2004].
[d]MLW = maximum landing weight.

Table 2 Tanker aircraft parameters

Refueling aircraft	MTOW, lb (N)	MFW, lb (N)	Cruise speed, M	Range, n miles (km)
747-400T	875,000 (3,892,000)	481,310 (2,140,867)	0.855	7,325 (13,566)
KC-5 Galaxy	840,000 (3,736,320)	332,500 (1,478,960)	0.790	2,400 (4,445)
KC-10[a]	590,000 (2,624,320)	342,000 (1,521,216)	0.825	4,400 (8,149)
767T	450,000 2,001,600	161,460 718,174	0.800	5,465 (10,121)

[a]Data available online at http://www.boeing.com/defensespace/military/kc10/kc10.htm [cited 16 Feb. 1998].

assumptions were made including an initial cruise altitude of 35,000 ft (10,668 m) and a fixed average fuel burn during cruise.

Tankers

Four aircraft were considered for the role of the tanker aircraft: a 747-400 tanker configuration designated as a 747-400T, a KC-5 Galaxy, a KC-10, and a 767 tanker, the latter based on the recent consideration of this aircraft for the U.S. military. Table 2 lists each aircrafts MTOW, maximum fuel weight, cruise speed, and range. The 747-400T was observed to be able to carry more fuel, faster and farther than all other alternatives. An alternate choice was the KC-10A Extender, an advanced tanker/cargo aircraft currently used by the U.S. Air Force. Although the operating cost of the KC-10A is arguably less, the 747-400T could carry a total of over 481,000 lb (2,139,488 N) of fuel, assuming all of the payload was also fuel, vs 342,000 lb (1,521,216 N) for the KC-10A. The 747-400 has a typical cruise speed of $M = 0.855$ as compared to $M = 0.825$ for the Extender, and it was desired to be able to refuel any commercial aircraft at cruise speeds. Hence, for the present study, a fictional 747-400T, equivalent to a 747-400 of Table 1, but modified to be a refueling tanker, was selected as the refueling aircraft. It was assumed that the 747-400T could deliver an amount of 481,310 lb (2,140,867 N) of fuel and transfer fuel at cruise altitudes and speeds.

Although not an off-the-shelf refueler configuration, 747 aircraft have been built as refuelers in the past, including a series sold to Iran in the early 1970s. An example of a view from the cockpit of a 747 being refueled by one of these aircraft is shown in Fig. 3.

Various other tanker specifications and mission conversion factors used in this analysis are listed in Table 3. Some are assumed, such as the tanker refuel time on the ground, while others are based

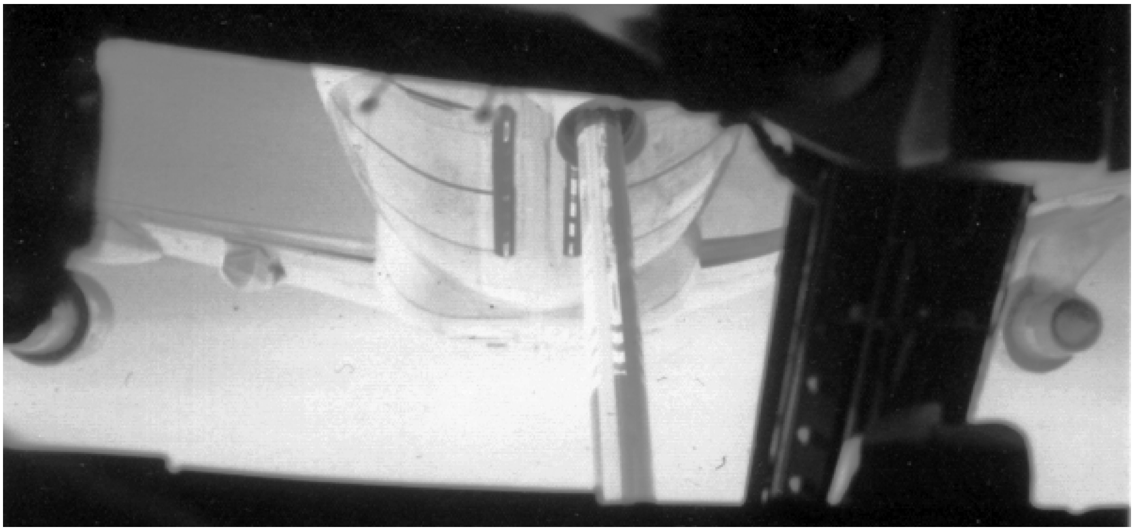

Fig. 3 Example of a 747 refueling a 747 (courtesy E. Tinoco, The Boeing Company).

Table 3 Refueling parameters for tanker aircraft (T)

Parameter	Value
747T Refueler Specs	
747T $/block hour[7]	$6,600
Initial maneuver time, min	10
Postmaneuver time, min	15
Refuel rate	
gal/min	1500
l/min	5678
747T req. reserves	
lb	26,000
N	11,565
747T req. climb fuel	
lb	26,000
N	11,565
Time to return, h	0.5
Tanker cost, $millons	$180
Tanker ground refuel time, h	1.5
Conversion factors	
Passenger loading	
lb/person	210
N/person	934
Fuel weight	
lb/gal	6.8
N/l	8.0
Est. rev./weight/dist.	
$/lb/nm	4.762E-04
$/N/km	5.781E-05
Standard day, h	12
Est. fuel cost	
$/gal	$2.00
$/l	$0.53

on published data, as in the $/block-hour costs to operate a 747-400 (Ref. 7). These data are further explained in the appropriate following sections, but are listed here together for a convenient reference.

Performance Analysis

The primary aim of this study was to determine the impact of increased payload, at the cost of off-loading fuel at takeoff and acquiring it sometime during flight, on the carrying capability of the aircraft for a given fixed range. The commercial software, Advanced Aircraft Analysis, based on the preliminary design techniques of Roskam,[8] was utilized to conduct parametric and optimization studies of simplified missions with a single refuel point at cruise using the preceding aircraft configurations. The method employs an iterative determination of the aircraft weight based on fuel required for a particular mission.

Each mission aircraft was simulated with specifications in Table 1, including 6.5% of total fuel kept as reserves at the end of the flight. The mission was defined to include the following segments: warm up, taxi, takeoff, climb, cruise, refuel, cruise, descent, and landing/taxi. Fuel fractions were determined for phase of the mission based on empirical values[8] or the Breguet equations along with estimates of the aircraft performance characteristics noted in Table 1. To create the baseline, no refuel case, the values of lift-to-drag ratio (L/D) and specific fuel consumption were varied until the weights reported by the manufacturer were matched. The refuel cases were then determined by varying the refuel point and iteratively adjusting the payload until the weights matched again.

Several restrictions were enforced at each phase of the flight. At the point in the mission where the refueling occurred, 2600 lb (11,656 N) of fuel were required to be onboard. This was defined as the minimum fuel presence at the beginning of refuel segment (MFPBRS), and would be used in case of any emergencies or inclement weather. It was assumed that the refuel point would be such that an alternate landing field was nearby in the event the tanker(s) failed to show. This 2600-lb MFPBRS, set to 6.5% of the total mission fuel for the A318, was kept constant for the other two aircraft resulting in 1.0% of the total mission fuel for the 777-300 and 0.7% of the total mission fuel for the 747-400.

Depending on the location of the refueling segment, each simulated mission was also limited by at least one of the following factors: maximum design taxi weight, MTOW, MLW, and maximum fuel volume. Mission refuel points of 0, 5, 25, 37.5, 50, 62.5, 70, 75, and 95% of the mission distance were examined for each case, along with additional values to find the optimums, for each airplane.

An example case of the 747-400 MA mission refueled at 50% of mission distance is given in Table 4, including the associated fuel fractions and the particular method of obtaining that fraction for each phase.

Mission Aircraft

The increase in payload capability for the 747-400 MA simulations are plotted in Fig. 4. At each point in the mission, the payload and refuel weights were varied iteratively to maximize the payload for that given refuel point until subject to one of the given constraints. The refuel weight at each point is listed along with the limiting factor which constrained that point. The maximum payload increase for this particular configuration was found to occur at 71% of the mission distance, enabling 205,482 lb (913,984 N) of payload to be carried, a 111% increase over its original carrying capacity of 97,500 lb (433,680 N). Note that there is a considerable plateau region, from 40 to 70% of the mission, where the payload carried only varies by less than 1%. This indicates that there is not much benefit over this range in terms of payload improvement; however, there are economic implications as will be shown later.

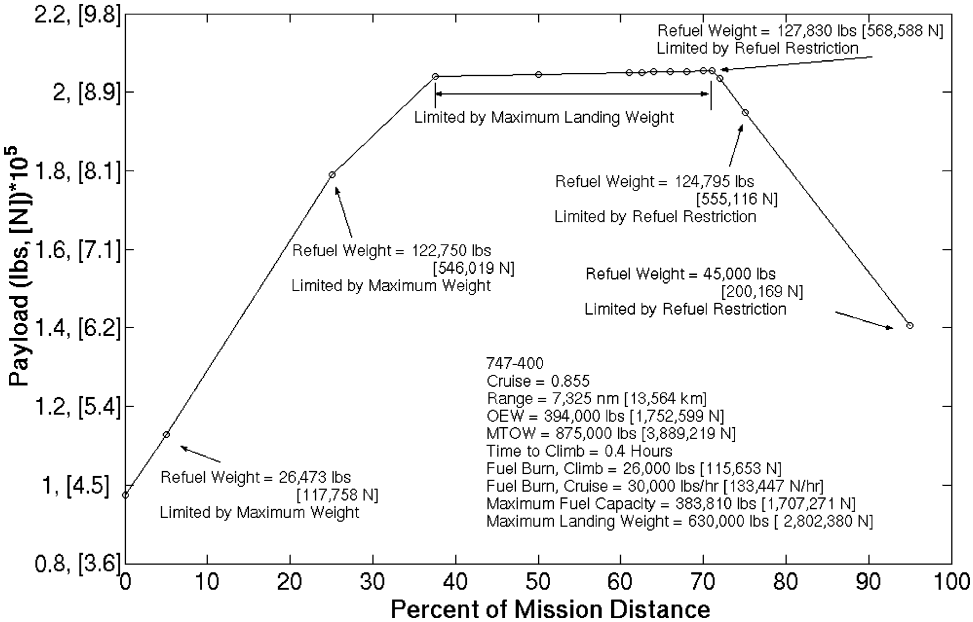

Fig. 4 Optimum refuel profile for 747-400.

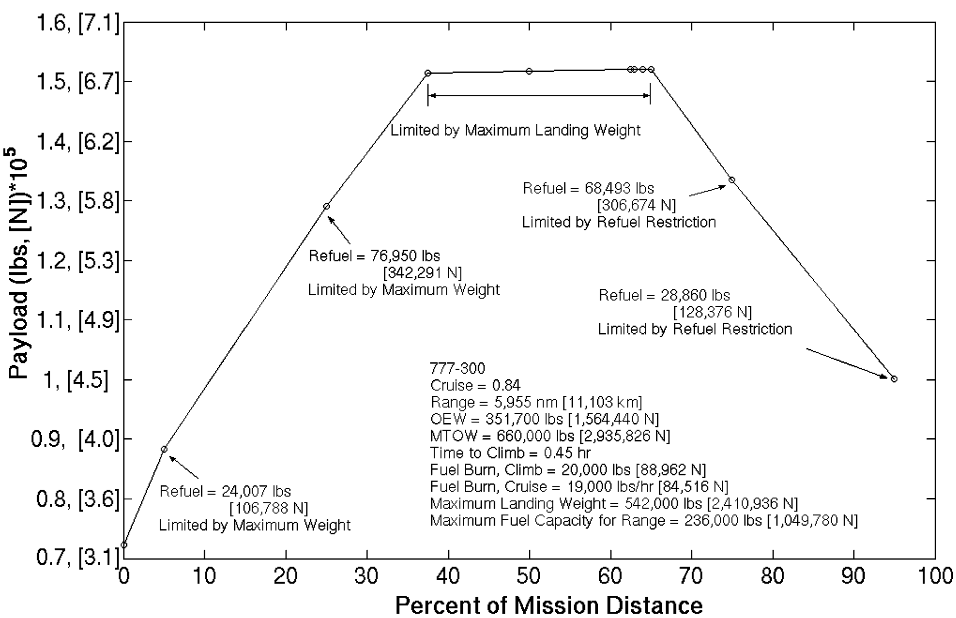

Fig. 5 Optimum refuel profile for 777-300.

Table 4 Mission flight phase example for 747-400 refueled at 50% mission distance

Mission profile	Mission fuel fraction, M_{ff}	Method of calculation
Warmup	0.9900	Roskam[8] empirical tables
Taxi	0.9900	Roskam[8] empirical tables
Takeoff	0.9960	Roskam[8] empirical tables
Climb	0.9944	Determined from distance to climb, rate of climb, specific fuel consumption, and estimated L/D value
Cruise	0.7858	Determined from range of cruise segment, speed, specific fuel consumption, and estimated L/D
Refuel	1.0000	Assumed to be unity as fuel is being added during this segment
Cruise	0.7858	Determined from range of cruise segment, speed, specific fuel consumption, and estimated L/D
Descent	0.9900	Roskam[8] empirical tables
Landing/taxi	0.9920	Roskam[8] empirical tables

Figures 5 and 6 illustrate the optimum refuel profiles for the 777 and A318, respectively. The optimum point for the 777 was seen to occur at 64% of the mission distance, enabling the aircraft to carry 152,042 lb (676,283 N) of payload, a 110% increase in payload capacity over the original 72,300 lb (321,590 N). A plateau region also exists, although it is smaller than the 747-400 case, spanning approximately 27% of the mission as opposed to 34% for the 747. The plateau region in Fig. 5 had a variation of about 3% in payload weight improvement. In contrast to this, the A318 model in Fig. 6 indicated almost no plateau region. The optimum refuel point occurred at 49% of the A318 mission resulting in a payload of 34,730 lb (154,479 N), a 88% increase over the baseline payload of 18,438 lb (82,012 N).

An important point to be made for each of these scenarios is that the amount of extra payload carried is not equal to the amount of fuel required to be added during flight. The simplified analysis of the previous study[6] set the refuel load the aircraft would require in the air to be equal to the increased payload at takeoff. Obviously, this is not the case because the weight of the aircraft with the increased payload will be greater in the post refuel portion of the

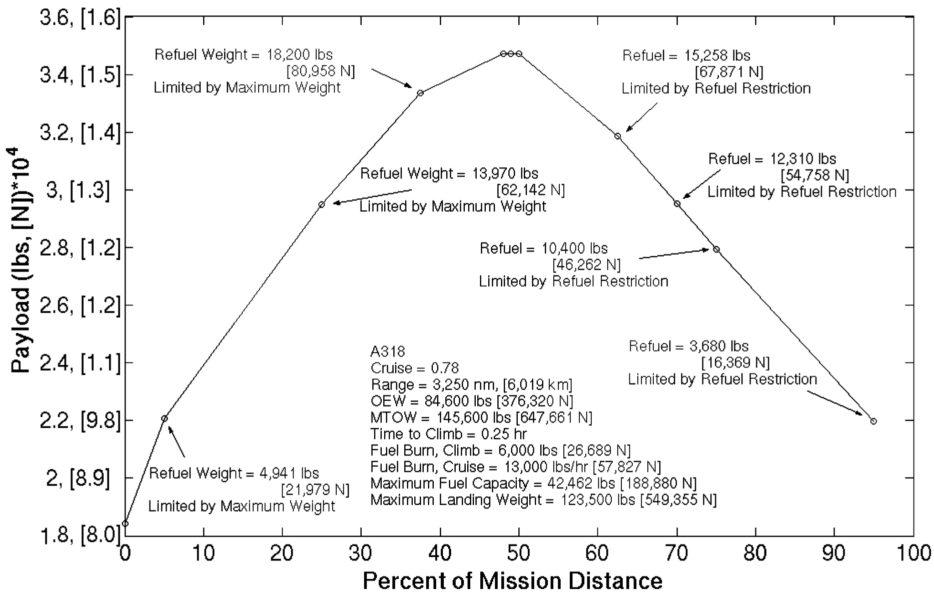

Fig. 6 Optimum refuel profile for A318.

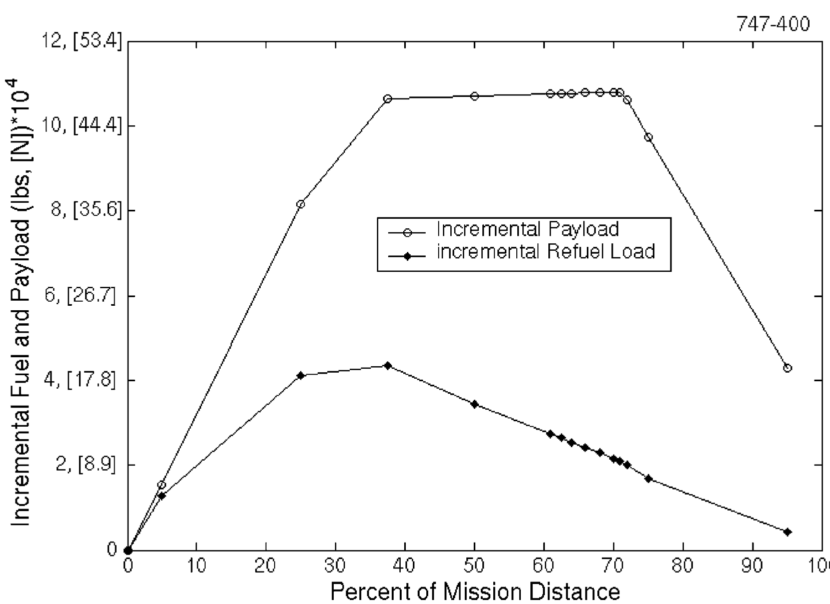

Fig. 7 Payload and refuel increments for 747-400.

flight than the conventional case. For example, consider the 50% refuel point of 747-400, with a payload of 204,546 lb (909,821 N), as compared to a conventional configuration 747-400 mission carrying 97,500 lb (433,680 N). Both missions take the same amount of fuel, 208,111 lb (925,678 N), to reach the halfway mark of the mission. However in the latter part of the mission, the refuel case requires 179,372 lb (797847 N) of fuel, whereas the normal configuration used 148,155 lb (658,993 N). The reason for this increase is that in a conventional aircraft mission the amount of fuel reduces over time, resulting in a lighter aircraft and increased performance. With the additional payload, however, this portion of the takeoff load does not decrease over time, requiring the refuel mission to consume more fuel. This is the basis for a refuel load increment that is greater than the takeoff payload increment.

This effect is illustrated in Fig. 7 for the 747-400. The increase in fuel required is plotted along with the increased payload as a function of refuel distance of the mission, the same abscissa as Figs. 4–6. This extra fuel represents an increased cost to the mission as well, which is discussed later on. Similar behavior was observed for the 777 and the A318, the latter of which is depicted in Fig. 8.

Note that the fuel increment required, as the mission traverses the plateau region of Fig. 7, decreases substantially. In other words, the fuel required to move almost the same payload is less if taken on later in the flight. This indicates that for a given increment in payload the point at which the refuel occurs to maximize the economic incentive is not necessarily that which maximizes the payload. This point is further emphasized by comparing fuel required directly against the given payload for the A318 in Fig. 9. For a given payload above the baseline, the amount of fuel required is strongly dependent on the refuel point in the mission.

Refueling Tanker

A simple model for the tanker was constructed based on typical values for a 747-400. This enabled an estimate of the number of mission aircraft that could be refueled for a given refuel load, the mission time for the tanker, and the number of missions the tanker could perform in a given day for a given fuel load.

An equation was first constructed to determine how many mission aircraft, MA, could be refueled by the tanker, T.

$$\text{Total T Fuel} = \text{Fuel for MA} + \text{T fuel consumed during refueling} + \text{T climb fuel} + \text{T reserves} \quad (1)$$

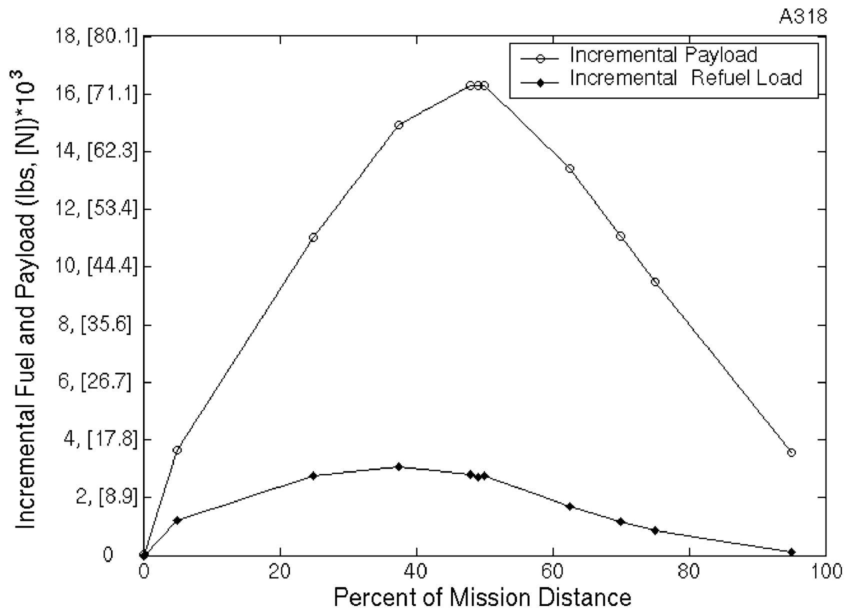

Fig. 8 Payload and refuel increments for A318.

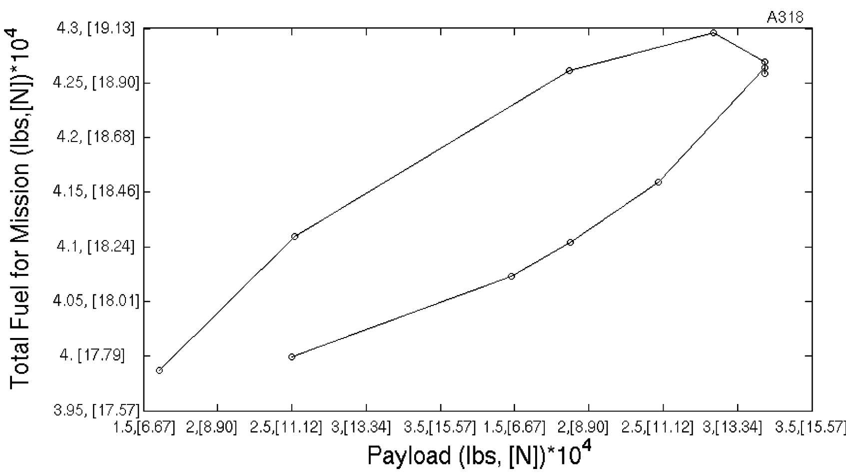

Fig. 9 Mission fuel requirement for A318.

Assuming approximately 26,000 lb (115,648 N) of fuel used by the 747-400T to reach cruise altitude and the same amount for fuel reserves, as noted in Table 2, Eq. (1) becomes

$$481 \text{ Klb} = (\text{MA} * \text{fuel required per MA}) + (30 \text{ Klb/h} * \text{Refuel Time/MA} * \text{MA}) + 26 \text{ Klb} + 26 \text{ Klb}$$

or

$$2139 \text{ KN} = (\text{MA} * \text{fuel required per MA}) + (133 \text{ KN/h} * \text{Refuel Time/MA} * \text{MA}) + 116 \text{ KN} + 116 \text{ KN}$$

To estimate the refuel time per MA (RT/MA), data from the Advanced Air Refueling Boom on the KC-10A, shown in Fig. 10, were used, which indicated refueling rates up to 1500 gal/min (5678 l/min), or about 10,200 lb/min (45,370 N/min).[§] Refuel time was then estimated from

$$\text{RT/MA} = \text{initial T maneuver time} + (\text{fuel required per MA/refuel rate}) + \text{post T maneuver time} \tag{2}$$

[§]Data available online at http://www.boeing.com/defensespace/military/kc10/kc10.htm [cited 16 Feb. 1998].

For example, a refuel load of 10 Klb (44 KN), along with estimates from Table 2, yields

$$\text{RT/MA} = 10 \text{ min} + (10 \text{ Klb [44 KN]}/(1500 \text{ gal/min} \times [5678 \text{ l/min}] * 6.8 \text{ lb/gal [8 N/l]}) + 15 \text{ min} \approx 26 \text{ min}$$

Note that the actual connect time is less than 1 min. It would appear that the rate of fuel transfer is not a limiting constraint, even with today's technology. Substituting this result into Eq. (1) and solving for MA yields a total of 18 possible 10 Klb (44 KN) MA refuels for a single tanker.

The mission time of the tanker can then be estimated from

$$\text{T Mission Time} = \text{Time to climb} + (\text{RT/MA} * \text{MA}) + \text{Time to return} \tag{3}$$

Assuming the time to climb = return time = 0.5 h from Table 2, a mission time of 8.7 h is required to refuel the 18 MA.

Using the preceding procedure, the number of missions per day, per single tanker, was determined for each point of the mission profiles in Figs. 4 and 5, based on a 12-h day and plotted in Fig. 11. It can be seen that as the required refuel weight increases with percent of the mission the number of mission aircraft that can be serviced by the tanker decreases because of the finite amount of fuel on the 747-400T. Once the maximum payload point of each profile is passed, the number of aircraft able to be refueled increases again.

Fig. 10 KC-10A advanced refueling boom (courtesy of The Boeing Company).

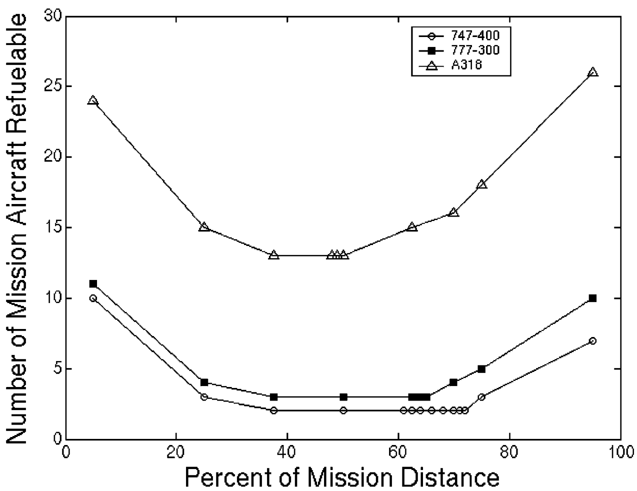

Fig. 11 Mission aircraft refuelable by a single tanker.

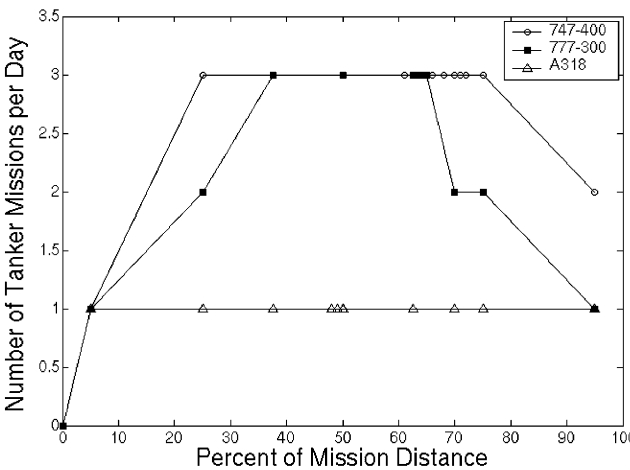

Fig. 12 Number of tanker missions per 12-h day.

The mission aircraft refuelable results for the 777 and the A318 are also presented in Fig. 11 along with the 747-400. Note that the number of A318 MA that can be refueled in a single tanker mission is substantially above that of the larger aircraft as it has a smaller fuel load. The results of this analysis were then used to evaluate each aircraft in terms of economic feasibility.

Economic Analysis

It goes without saying that if no profit were to be made, the concept of commercial aerial refueling would never get off the ground, even if the technological challenges were met. The most obvious costs include the need for an additional tanker aircraft, crew, and the associated operating costs. The means of placing the fuel in the sky could take different forms, from airline consortiums to private suppliers. For the purpose of this study, it is assumed that the infrastructure is already in operation and the nonrecurring startup costs associated with this will not be estimated here. There are also additional intangible benefits that are not accounted for here. For instance the "payoff" of being able to fly point to point anywhere on the globe can have a large impact on aircraft sales. Some of these benefits are listed in the following section for further consideration.

To estimate the economic potential of the preceding concept, each of the configurations mentioned earlier was now examined in light of the payload capabilities illustrated in Figs. 4–6 and the number of MA refuelables from Fig. 11. First, the total number of refueling missions a single tanker could perform in a given day was determined. Assuming a 12-h standard day, the number of tanker missions, which includes the time requirement to return to base, refuel the tanker, and return to the transfer point, is plotted in Fig. 12 against mission point for each of the aircraft. This value indicates the number of missions a tanker can make in a day with that tanker able to service the number of MA based on their fuel requirements. It can be seen that although more aircraft can be serviced if each requires a smaller load, more fuel volume can be moved from the tanker in a given operational day if the fuel transfer loads are larger. Figure 12 illustrates that a 747-400T will only require one mission per day when refueling the A318. This is caused by the long mission time associated with refueling 13 or more A318 aircraft for each mission pictured in Fig. 6. The economic model does not allow for partial missions to be run, and therefore, after completing say an eight-hour mission, refueling 13 plus aircraft, the tanker could complete no further missions.

It was assumed that, at the very least, a minimum of two tankers is required for a viable tanker operation at an estimated cost of $180 million dollars each. If one tanker should be down for repairs, the other could be dispatched to refuel planes. Operational costs for the 747-400T were estimated at approximately $6600/block hr based on airline data in Ref. 7. This includes operations, maintenance, and depreciation costs. To estimate revenue from the increased payload, a factor with units of $/lb/mile was determined based on nominal estimates of $200/210 lb (934 N) passenger load/2000 n miles

(3704 km) trip or 4.762E-04 \$/lb/n miles (5.781E-05 \$/N/km). Table 3 summarizes the parameters used for this analysis.

The equation for tanker costs in \$/day (TCPD) was constructed according to

$$\begin{aligned}\text{TCPD (\$/day)} &= (\text{Missions/day} * \text{Mission Time} \\ &\quad + \text{Ground Refuels/day} * \text{Ground Refuel Time}) \\ &\quad * \text{\$/block hour}\end{aligned} \tag{4}$$

where the number of ground refuels is one less than the number of missions. The estimated gross revenue per day (GRPD) is determined from

$$\begin{aligned}\text{GRPD (\$/day)} &= (\text{Missions/day} * \text{MA Refueled} \\ &\quad * \text{Revenue/lb/mi} * \text{Refuel Load} * \text{Range})\end{aligned} \tag{5}$$

This equation is good for both the range and payload cases, where the payload is kept constant in the former and the range kept constant in the latter; however, only payload cases are considered in the present study. As a first estimate, the net revenue is simply taken as the difference of these two values minus the incremental fuel cost for the refuel trip.

$$\begin{aligned}&\text{Net Revenue(\$/day)} \\ &\quad = \text{GRPD} - \text{TCPD} - \text{Incremental fuel} * \text{Fuel cost}\end{aligned} \tag{6}$$

The associated refuel time per mission is then calculated for each case. This determines the increment in payload movable per day as well as the time required for the tanker to be in service.

The net revenue per day as a result of increased payload capability is shown in Fig. 13 for the 747-400. The maximum amount of revenue per day occurs at the 25% mission point, corresponding to a 122,000-lb (542,656-N) refuel load. Although the optimum refuel point in terms of maximum payload moved, at 71%, might have been be surmised to be better economically, the decrease in the number of mission aircraft refuelable from the tanker causes it to be economically inferior. A higher capacity tanker vehicle could change this significantly.

The net revenue per day can then be used to calculate the amount of time before two 747-400T tankers can be paid off. Figure 14 illustrates a simple payback period, based on the revenue of Fig. 13, for the original cost of the tankers. As noted before, this does not account for initial infrastructure cost associated with such an operation, nor is the calculation done with any sophisticated economic model. The optimum occurs, as might be expected, at the mission point that generates the most revenue per day, but also even for most of the mission points, the simple payback indicates less than one-half of a year to recover the tanker investment.

Net revenue per day for the 777-300 was of a similar magnitude to the 747-400, but occurred at a different mission point of 37.5% corresponding to a refuel amount of 102,500 lb (455,920 N) as shown in

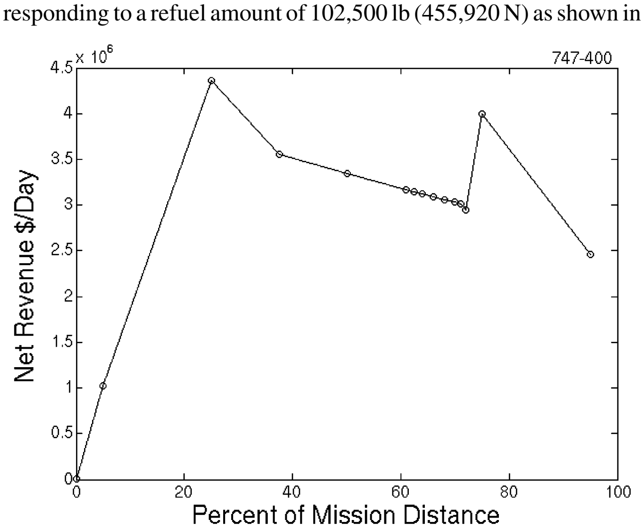

Fig. 13 Net revenue per day for 747-400 mission aircraft.

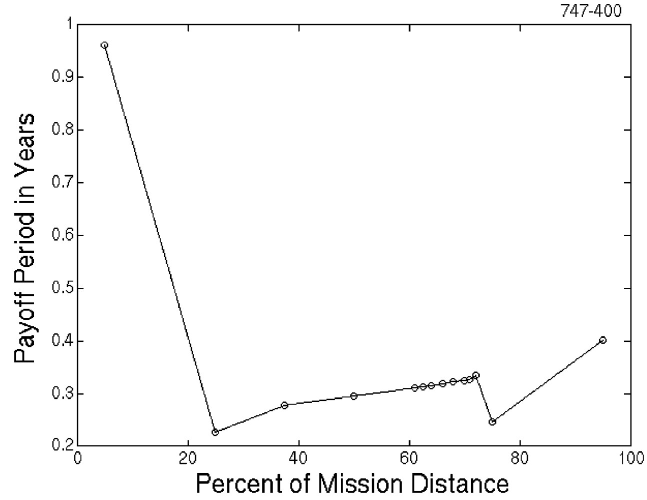

Fig. 14 Simple payback for 747-400 mission aircraft.

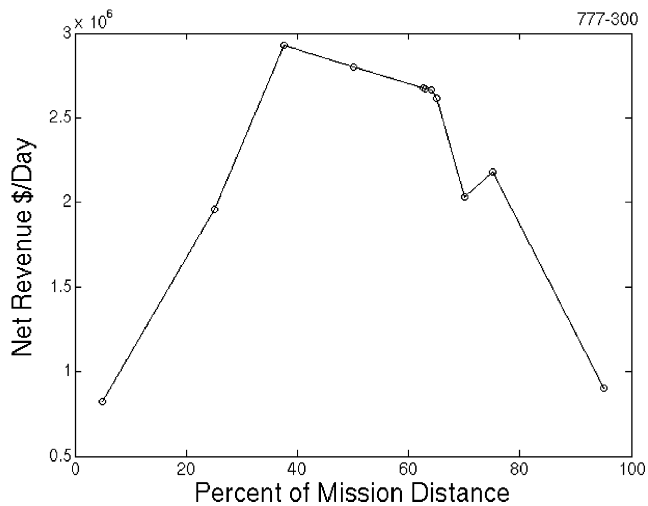

Fig. 15 Net revenue per day for 777-300 mission aircraft.

Fig. 15. This was also not at the maximum payload point. The maximum net revenue corresponds to three MA refuelable per tanker mission and three tanker missions in the 12-h day per day. The simple payback for the 777 is similar to the 747 as the maximum revenue per day is on the same order of several million dollars per day.

The behavior of the A318 differed substantially from the larger aircraft as it is able to have many more mission aircraft refuelable from a single tanker mission. As illustrated in Fig. 11, the lowest number of missions was 13, as compared to that of three for the 777-300. This is a result of the A318 needing a smaller amount of fuel in order to complete the mission, which also has a smaller range. Although not examined here, a more complex model that would incorporate a range capability above that of the no-refuel range would be interesting.

Despite a greater number of missions run per day, the A318 cannot generate near the revenue per day as the 777-300 or 747-400. Figure 16 depicts the A318 net revenue per day with a maximum of about \$400,000, an order of magnitude below that of the other two aircraft. As a result of the decreased net revenue, it takes a greater amount of time to payoff the two tankers, requiring about two-and-a-half years to complete a simple payback as Fig. 17 shows. An interesting issue that differentiates this size of aircraft from the larger ones is that the maximum revenue point corresponds to the optimum refuel point.

Implementation Issues

Several major issues, in particular that of safety, would need to be addressed if aerial refueling of commercial aircraft were ever to

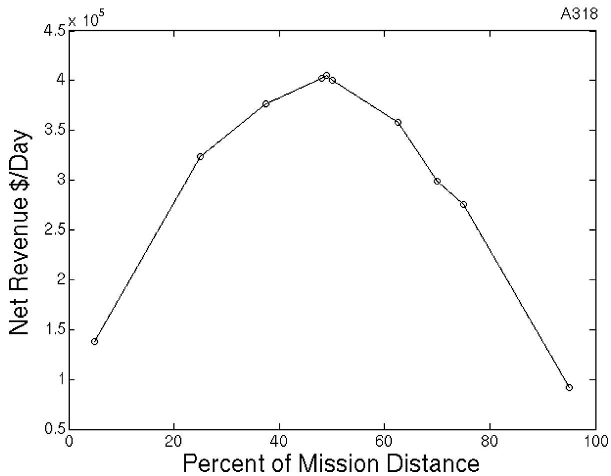

Fig. 16 Net revenue per day for A318 mission aircraft.

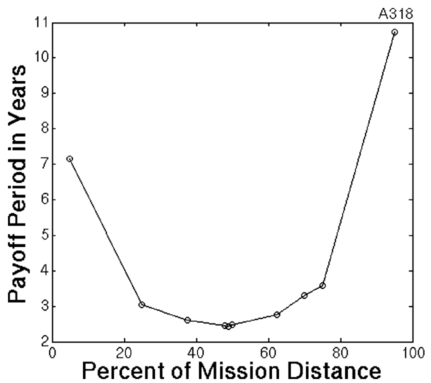

Fig. 17 Simple payback for A318.

become a reality. The U.S. Air Force refuels aircraft, both fighters and wide-body aircraft, as shown in Fig. 1, on a daily routine basis, and it is reasonable to think this can be extended to commercial aircraft. Modifications to current refueling procedures would undoubtedly be required for commercial implementation, and some suggestions for these are discussed next.

Feasibility

The preceding arguments make several assumptions that need to be realized if such a concept is to be realistically implemented. The first is whether or not the payload increases proposed would be realistically feasible on the given aircraft. The 747-400 is capable of carrying a total of 5600 ft^3 (158.6 m^3) below decks in the form of 16 full-width LD2 containers for a gross weight of 112,000 lb (3171.5 N) or 20 lb/ft^3 (134.4 N/m^3). An additional 835 ft^3 (23.6 m^3) can be carried in the bulk cargo compartment for an estimated weight, based on the 20 lb/ft^3 (134.4 N/m^3), of 16,700 lb (74,281.6 N). Thus, the total possible payload that can be carried below decks is about 128,700 lb (572,457.6 N), based on data from the website in the footnote.[¶] The maximum amount of payload from the present study was observed to be 205,482 lb (913,983.9 N) or an increase of 107,982 lb (480,303.9 N) above the baseline 97,500 lb (433,680 N), well below 128,700 lbs (572,457.6 N). Hence, it appears that this scenario is physically possible.

The 777 can hold 7552 ft^3 (213.8 m^3) below decks. No data were found in the website in the footnote[**] as to the maximum load limits; however, based on the 20 lb/ft^3 (134.4 N/m^3) from the 747 data, a total of 141,600 lb (629,836.8 N) can be accommodated. As it only needs 79,742 lb (354,692.4 N) to meet the optimum refuel requirements of the current study, this scenario also appears feasible.

The A318 can carry 749 ft^3 (21.2 m^3) in bulk cargo for an estimated 14,980 lb [based on the 20 lb/ft^3 (134.4 N/m^3) from the 747], which is not quite the 16,292 lb (72466.8 N) maximum the study suggested. The present study considered an 88-passenger payload for the A318, and the website in the last footnote[††] suggests it can seat 107 in a two-class setting. Hence the additional payload could also be in the form of more seats, say 19 for a payload increase of 3990 lb (17,747.5 N) above decks, in addition to the 14,980 lb (66,631 N) below, well above the 16292 lb (72466.8 N) noted earlier.

Although all three cases examined indicate feasibility from a physical capacity point of view, it is useful to examine whether the revenue rate estimates for the increased cargo are also valid. Costs were obtained from a national carrier to transport cargo in the form of 210 lb (934 N) equivalent passenger increments. For a distance of slightly under 2000 n miles (3704 km), the cost to transport two 105-lb (467-N) packages of a volume that would be occupied by a passenger and luggage was found to be greater than twice the $200 figure used in the present analysis for second-day air delivery and more than $600 for next day service. Although these values reflect a retail rate to individuals and small companies, as opposed to larger contracts with a carrier, it suggests that the $200 passenger rate, itself a fairly conservative value, is acceptable for the cargo increments in the present analysis.

Systems

Current U.S. Air Force aerial tankers utilize a refueling crew member seated at a station with windows in the aft section of the aircraft, as in the KC-10A pictured in Fig. 10, or in the prone position if refueling from a KC-135R aircraft. Those systems rely on the naked eye to directly guide the boom for refueling to the aircraft following behind. A system that could be effectively employed in the commercial market might benefit by a completely different refuel philosophy whereby the tanker approaches the mission aircraft from behind, instead of the conventional procedure used in todays military operations. The tanker would refuel the MA from behind instead of having the MA follow the tanker to refuel. The MA pilots continue to fly their mission at cruise speeds, whereas the tanker focuses on the maneuvering aspects of the refuel operation, the attachment, fuel transfer, and breakaway.

State-of-the-art systems, such as remote aerial refueling operation (RARO) system offered by Boeing, enable operator control from the forward main deck of the aircraft.[9] RARO includes three-dimensional operator displays and plus remote sensors that allow wing-tip-to-wing-tip viewing of the area aft of the tanker. With the remote operating concept the refueling crew member uses a closed-circuit video camera and monitoring system to view the air refueling operation. The RARO system provides night vision, improved vision in poor weather conditions, and enhanced depth perception because of the camera's stereoscopic and infrared capabilities.

NASA Dryden and the Defense Advanced Research Projects Agency are presently exploring automated aerial refueling to enable unmanned aerial vehicles (UAVs) to refuel from tankers in flight.[‡‡] Understanding the flight dynamics and aerodynamic interactions is the goal of this study before automated UAV refueling is a reality.

Technology also exists today that would enable the airplanes to be "locked together" electronically in flight to provide automatic stationkeeping and even automatic refueling.[10,11] The refueling boom could even be designed to extend forward, rather than the present aft-extended designs, similar to the flying strut/boom currently used in the Boeing Transonic Wind Tunnel.[12]

Safety

In the past, crossing the Atlantic in a commercial flight with only two engines would have been unthinkable. Yet, today, no one even

[¶]Data available online at http://www.boeing.com/assocproducts/aircompat/acaps/747_4.pdf [cited 12 Jan. 2004].

[**]Data available online at http://www.boeing.com/assocproducts/aircompat/acaps/777_23.pdf [cited 12 Jan. 2004].

[††]Data available online at http://www.airbus.com/product/a318_specifications.asp [cited 12 Jan. 2004] and http://www.airbus.com/product/a318_performance.asp [cited 12 Jan. 2004].

[‡‡]Data available online at http://www.dfrc.nasa.gov/Newsroom/ResearchUpdate/AAR/index.html [cited 12 Jan. 2004].

pauses to count the engines when they step into a plane to fly from New York to Paris. In the same way, an acceptably low risk level by the public is the key to the success of commercial aerial refueling.

A means to implement such a revolution in air travel procedures might be to begin with the cargo industry. Parcel delivery carriers could find the idea of such payload extensions to be very attractive and with a much lower risk factor than a plane full of passengers. In this way, aerial refueling waypoints, routes, and infrastructure could be established and a proven safety record established in the commercial sector before the introduction of this concept for passenger travel.

Additional Benefits

There are many benefits, especially intangible ones, associated with midair refueling that are difficult to quantify numerically. Listed next are several that would need to be considered including benefits for the possibility of increased range capability.

Increased Revenue for Aircraft Manufacturers

Aircraft manufacturers would have a larger market for tanker aircraft, perhaps even larger aircraft than the 747 example used here. Manufacturers could offer refuel options, and modifications, on every production aircraft, as well as retrofit kits for in-service aircraft. Civilian aircraft sales in general could increase as the appealing consideration of unlimited range in the world is realized.

Increased Revenue for the Airlines

Airlines would benefit from such an aerial refuel concept in several ways: 1) more revenue flight hours/day by flying directly to destination and avoiding stopovers, 2) reduced landing fees by bypassing airports, 3) lower maintenance costs and increased airframe life cycle from a decrease in cycles/trip, 4) congestion alleviation at airport hubs from point-to-point improvements, 5) takeoff from shorter field lengths with larger payloads, and 6) noise reduction capabilities.

Revolution in Future Commercial Aircraft Design

Perhaps much more tantalizing than any of the points just mentioned, however, is where the implementation of aerial refueling would lead. If the possibility existed that a commercial aircraft could be designed so as not to have to carry all of the fuel aboard for the entire mission, there would be a revolution in airplane design. Increasingly high development costs have forced most aircraft manufacturers to focus on minimum change derivatives of current production aircraft as opposed to all new designs. The recent 777 and A380 are exceptions to this, in a sense, but novel commercial designs seem to be a thing of the past, and this tends to dampen enthusiasm and imagination of young aeronautical engineers in the aircraft industry.

The refueling benefits discussed thus far refer to the first cycle implementation of such an idea, which utilizes existing aircraft to enable this capability. Removing the restriction of carrying all of the fuel onboard for a given mission, however, opens up all kinds of design possibilities. For example, a reduction in the required fuel load could result in a reduction of the structural weight of an extended range aircraft. The option to obtain fuel in the air would reduce the required engine thrust takeoff, which would reduce engine weight. Noise would also be reduced on takeoff, as less thrust would be required, and the impact on future aircraft such as a very long-range transport or a supersonic transport aircraft could be enormous. All of these factors would serve to increase performance and cycle into the design to result in even better performance for the new aircraft.

Conclusions

The concept of aerial refueling for commercial aircraft has been briefly discussed using a mission performance simulation program and a simplified economic model. The impact on mission capability and economics from an increased payload, as a result of fuel offset at takeoff, was examined for three different aircraft: a 747-400, a 777-300, and an Airbus A318, using a 747-400 as the tanker. Several specific conclusions were reached:

1) An optimum mission distance refuel point to maximize payload was determined for each aircraft: A318 at 49%, 777-300 at 64%, and 747-400 at 71%. The associated maximum payload improvements were in 88, 110, and 111%, respectively.

2) Smaller mission aircraft refuel loads would enable the service of more aircraft from a given tanker; however, much more fuel can be moved with larger refuel loads as the refuel connect time is not the limiting factor.

3) It is more economically viable to refuel larger airplanes such as the 747-400 and 777-300.

4) The maximum net revenue per day does not necessarily exist at the optimum refuel point.

5) Intangible benefits are large and need to be accounted for in addition to economic value.

6) A change in the current methods for refueling aircraft would probably have to be implemented to enable commercial aerial refueling.

7) The possibility of a revolution in aircraft design exists as a second cycle benefit to the implementation of commercial aerial refueling.

It is proposed that the first cycle benefits of in-flight refueling being the use and modification of existing aircraft to enable this capability, would result in substantial changes in air transport capabilities. Additional perceived benefits include increased revenue to both the manufacturers and the airline operators, in the form of more product options, more revenue flight hours, and increased airframe life. A second, more far reaching impact exists, where the implementation of in-flight refueling would result in a subsequent change in the way airplanes are designed, and even conceived of, to take advantage of this opportunity. This possibility of an empty design canvas and an uncharted design space, enabled by a global aerial refueling capability, is certain to stir the imagination of present and future aircraft designers.

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