CONCEPTUAL DESIGN OF A PASSENGER AIRCRAFT FOR AERIAL REFUELING OPERATIONS

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Keywords: *RECREATE, cruiser/feeder, aerial refueling, tanker, staging flight*

Abstract

The European project RECREATE (REsearch on a CRuiser Enabled Air Transport Environment) is investigating the design of new passenger aircraft and operation paradigms to drastically reduce fuel consumption and gas emission. One of the proposed concepts concerns with the introduction of air-to-air refueling between passenger aircraft (cruisers) and tanker aircraft (feeders). This paper focuses on the conceptual design of the cruiser and compares its performance with that of existing aircraft and others specifically designed to perform the same transportation mission, using direct and staging flight. AAR operations yield a potential fuel saving in the order of 15% with respect to direct flight (including the fuel used by the tanker) when specifically designed cruiser and tanker aircraft are employed to transport 250 passengers over a range of 5000nm, with one aerial refueling. Marginal fuel saving can be achieved also with respect to staging flight operations (i.e. intermediate refueling stops).

1 Air-to-air refueling operations for passenger aircraft

In order to meet the challenging targets on environmental impact set by ACARE [1], it is necessary to investigate innovative aircraft designs and operational paradigms. One of the concepts currently investigated within the European project RECREATE (REsearch on a CRuiser Enabled Air Transport Environment, www.cruiser-feeder.eu) is the adoption of aerial refueling for passenger transportation. The basic idea is that by splitting a flight mission in more sections and making use of air-to-air refueling operations (AAR), it is possible for aircraft to take off lighter and fly much more efficiently. Besides that, smaller lifting surfaces and engines would be sufficient, thereby reducing even further the mass of the aircraft designed to perform such a mission, hence the required fuel, according to the well-known snow ball effect on weight.

The potential fuel savings achievable by "burning less fuel to transport fuel" have been analyzed in several studies, addressing different operational contexts and missions [2, 3]. In particular, there are a number of studies that demonstrate the convenience of splitting a long range mission into shorter stages by means of intermediate refueling stops, i.e., by *staging flight* [4-6]. Maximum fuel savings up to 40% have been estimated, although very dependent on the mission flown and the type of used aircraft, either an existing one or one designed on purpose. Although staging flight is convenient in terms of fuel saving and related emissions, it has a significant impact on the total mission duration and the aging of aircraft, due to the increased frequency of air-ground cycles. These shortcomings make staging flight unattractive to passengers and operators.

Differently, AAR operations could deliver the advantages of staging flight without the mentioned limitations. Although this operational concept is more complex than staging flight, it still appears to be a viable short term technical solution to reduce fuel consumption.

The introduction of AAR operation in civil transportation can leverage on the long standing experience in military aviation. However, new and different requirements such as passenger comfort and safety, costs, economics, pilot training and others might demand a different way of performing AAR when passenger aircraft are involved. *In what extent is possible to adopt the consolidated AAR military approach into passenger aircraft operations?* This is the first research question for this study, specifically addressed in Section 2.

The second question concerns with the configuration characteristics of a passenger aircraft specifically developed for AAR operations. *Is a new design necessary or would it be possible to achieve fuel savings even using existing aircraft?* The conceptual design of a specifically dedicated cruiser aircraft is elaborated in Section 3; the comparison of its performance indicators with those of existing reference aircraft in discussed in Section 4.1.

The final question addressed in this work is about the achievable fuel saving: *how much fuel can be saved by implementing the AAR operational approach with respect to direct and staging flight?* The estimation of the net fuel saving provided by AAR requires the performance analysis of the tanker operations. The lower the tanker efficiency factor (defined as the ratio between the fuel delivered and the fuel burnt by the tanker), the lower the AAR advantages with respect to direct and staging flight. Although the description of the refuel scheduling strategy and logistics, and the design of dedicated tankers (or the adoption of existing ones) are outside the scope of this paper, the final results are provided in Section 5. Reference to other RECREATE publications is provided to allow the reader appreciating the whole scope of the research project.

2 Rethinking the AAR cruiser-feeder configuration

Aerial refueling is a well consolidated operation in military aviation, where one tanker serves one or more receivers that fly behind and below. However, the adoption of AAR operations for passenger aircraft has demanded the analysis of alternative configurations that could account for the different criteria (passenger safety and comfort, crew training, etc.). To this purpose a tradeoff process has been performed in the early phase of the RECREATE project, to compare alternative cruiser-feeder flight formations, with the cruiser flying ahead or behind the tanker; above, below, in line or laterally staggered. Both the use of flying boom and probe and drogue systems has been considered, in combination with various options for the location of the receiver refueling point. The tradeoff criteria were set on the basis of such considerations as:

- Safety of the passengers in case of accidental detachment of (part of) the refueling system
- Sufficient clearance between cruiser and feeder with possibility for safe separation
- Minimum discomfort for passengers during refueling (due to maneuvers and noise),
- Minimum additional weight and space reservation penalty on the cruiser
- Minimum workload and additional training for the cruiser crew
- Minimum impact on cruiser engine sizing (flying in the downwash of the leading aircraft, at cruise speed and altitude, demands extra thrust as for climbing)

All possible formations and refueling systems configurations have been examined assuming the AAR maneuver to be performed at cruise conditions (M0.82 @ 10500m). This is much more demanding than in current military applications, but it was deemed necessary not to spoil the advantages of AAR by adding descend, deceleration and climb stages to the mission.

The performed tradeoff indicated the convenience to adopt an AAR refueling configuration where the tanker flies below and behind the receiving aircraft and mounts on the foretop of its fuselage a flying boom, which can be deployed against wind and gravity (Fig. 1).

This configuration ranked first in the tradeoff notwithstanding the low score attributed to the feasibility of the forward extending boom. While the use of a relative small pump was estimated sufficient to transfer the fuel against gravity, the unusual boom configuration was expected to present static and dynamic stability challenges.

To this purpose, next to the conceptual design of cruiser and tanker, a feasibility study of the novel boom was initiated. Some details in Section 2.1.

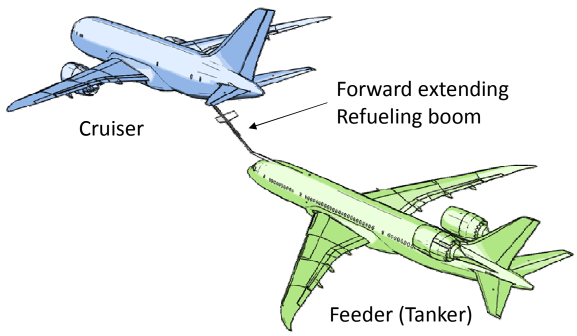

Fig. 1 Tanker (feeder) flying below and behind the cruiser during AAR

2.1 Development of a forward extending refueling boom

The main challenge associated to design of the forward extending boom is its inherent instability. Problem of structural divergence and flutter can make this concept unfeasible or much heavier and more complex than a conventional afterward-extending boom. To this purpose a number of design options have been considered, based on different kinematic solutions and materials. A multidisciplinary design optimization framework was developed to size more than 10 boom variants, all based on a 4 ruddevators configuration to fly the boom within the required envelope. While some of the variants appeared to be infeasible (structural divergence), it was possible to obtain a working solution based on the roll actuated mechanism illustrated in Fig. 2. Both the composite and aluminium versions of this boom variant appeared to be fully controllable, and free of static and dynamic structural divergence within the operational conditions and configurations prescribed by Certification Specifications. The weight and drag contribution of the boom appeared also comparable with those of the KC-135 boom, which was used as reference. Details of the forward extending boom design are provided in ref. [7, 8].

3 Conceptual design of the cruiser

On the basis of the selected AAR configuration, it was possible to design the cruiser aircraft without the need to account for any particular requirement, either related to the integration of the refueling system, or any special maneuvering during refueling. Table 1 lists the cruiser top level parameters defined by the RECREATE consortium.

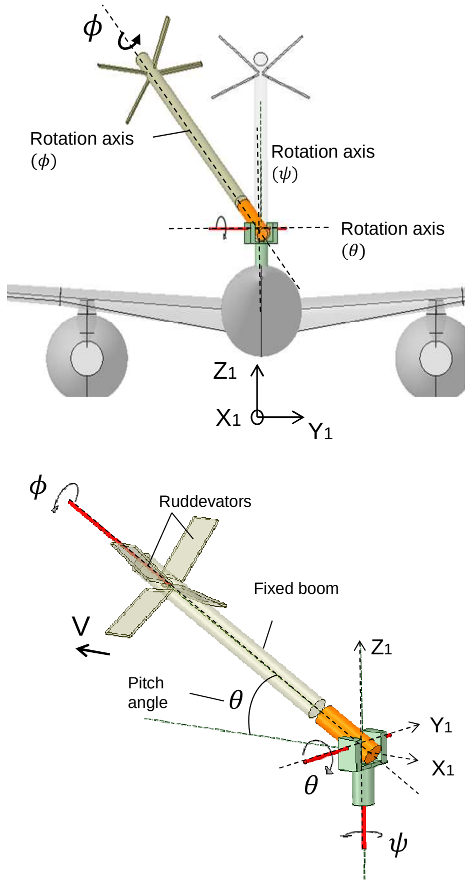

Fig. 2 Schematic representation of the roll actuated boom configuration

The relatively low specific fuel consumption of the engine was selected accounting for the trend in fuel efficiency of turbofan engines. The takeoff and landing field length allows the cruiser to operate also on relatively small airports, including the tanker bases, which can be used as alternative airports in case of emergency.

It was decided to design a conventional aircraft configuration, with cylindrical fuselage and cantilever wing, aiming at a short term introduction of the AAR concept in civil aviation.

The peculiar combination of payload requirements, typical of a twin aisle medium range aircraft such as the A330 or the B767, and range requirements, typical of a single aisle short range jetliner such as the B737, are the cause of the peculiar cruiser shape, which features a relatively small wing (and tail) when compared with its fuselage size (Fig. 3). The cruiser difference with respect to "regular" aircraft can be better appreciated in Section 4.

Payload	• 250 Pax at 106kg (incl. luggage • No additional freight, but cargo hold sized for LD3 containers
Total range	9260km (5000nm)
Number of refueling	1 (around 2500nm)
Cruise speed	M0.82 @ 10500m (35000ft)
Engine technology	SFC = 0.525l/h
Cabin Comfort	Twin aisle, single class • Seat pitch > 85cm • Seat width > 51cm • Aisle width > 50cm
Takeoff and landing performance	2500m BFL according to CS
Climbing gradient	According to CS
Climbing rate	348m/min (OEI)

Table 1 cruiser top level requirements

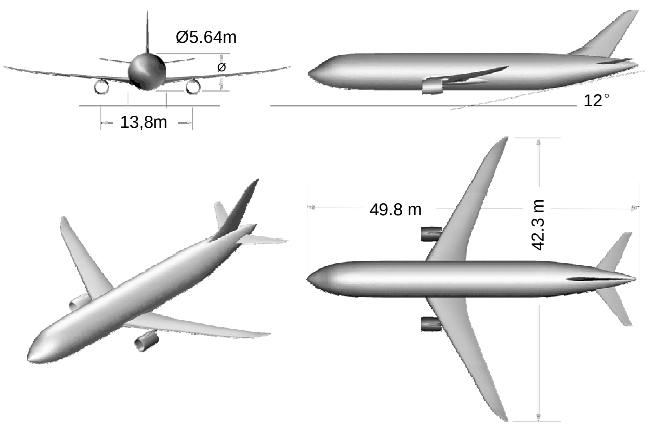

Fig. 3 the RECREATE cruiser

The conceptual design of the cruiser was performed with the support of two in-house developed aircraft design tools, called the Initiator and AC-X, whose main functionalities are described in ref. [9, 10] and ref. [11], respectively. The common characteristic of these two software tools stands in their ability to address the design of both conventional and unconventional design, such as joint-wing, blended wing body aircraft, canard and three lifting surfaces airplanes. Both have a modular structure and make use of several semi-analytical or simulation based analysis tools, in place of the typical semi-empirical, statistic-based methods, which are generally suitable for the synthesis of conventional airplanes but unable to capture the peculiarities of non-conventional configurations. For example, they both make use of the engine sizing method described in ref. [12]. For the aerodynamic analysis the Initiator makes use of the Athena Vortex Lattice (AVL) (http://web.mit.edu/drela/Public/web/avl/), while AC-X makes use of response surfaces generated on the basis of full CDF simulations. For the weight estimation of the wing and fuselage components, the Initiator makes use of two in-house developed semi-analytical tools [13, 14] that are much more design sensitive than classical Class II methods. Whilst the Initiator works mostly in batch mode and can be plugged to an optimizer, AC-X allows for more designer interaction.

Both tools have been used to design the cruiser, also in view of comparing their performance. Table 2 reports the obtained geometry and performance parameters of the cruiser, as designed for point D (see payload range diagram in Fig. 4).

OEW [kg]	52,589
MTOW [kg]	100,865
OEW / MTOW	0.52
Total mission fuel weight [kg]	32,929
Fuel necessary via AAR [kg]	14,505
Fuel reservation [kg] (250nm diversion and 30 minutes loitering)	3,352
T / MTOW	0.3
Wing Area [m^2]	164
Span [m]	42.4
Aspect Ratio	11
Cruise L/D	16.2
PRE [nm]	4,024
X [nm]	14,409

Table 2 cruiser parameters

The choice of this design point allows for the cruiser to offer a good level of operational flexibility. For example, it can fly shorter cruise mission while carrying extra freight (point A) or longer mission with a 3 class cabin configuration

(Point D to B and C). At point A, the fuselage holds are not completely filled. Filling them completely would reduce so much the allowed mass of fuel (to reach MTOW) that only extremely short missions of no practical interest would be possible. Therefore Point A was set by imposing an artificial minimum range requirement. This indicates that the available cargo volume is actually too large and the LD3 sizing requirement should be revised in the next design iteration.

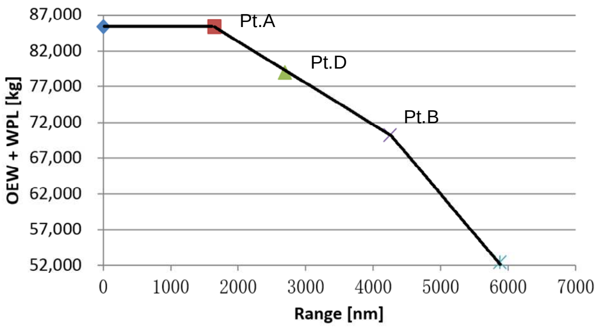

Fig. 4 Payload-Range diagram of the cruiser

The parameters PRE and X are two common indicators that allow comparing the transport efficiency and technological level of different aircraft (or aircraft operating at different points in their payload range diagram)[3]. The Payload Range Efficiency (PRE) is defined in (1).

$$PRE = WP*R/WFB \ (nm) \qquad (1)$$

WP is the payload weigh, R the range and WFB the block fuel weight.
The range parameter (X) defined in (2) follows from the usual Breguet range equation:

$$X = (V*L/D)/SFC \ (nm) \qquad (2)$$

V is the aircraft cruise speed, (L/D) the aerodynamic efficiency in cruise, SFC the engine specific fuel consumption.
The plot in Fig. 5 highlights the very high PRE value achieved by the cruiser (at point D), even when compared with the PRE of existing aircraft operating at Point A (which typically yields the largest PRE value). This result is the consequence of the very low value of WFB, despite the relative poor aerodynamic efficiency of the cruiser.

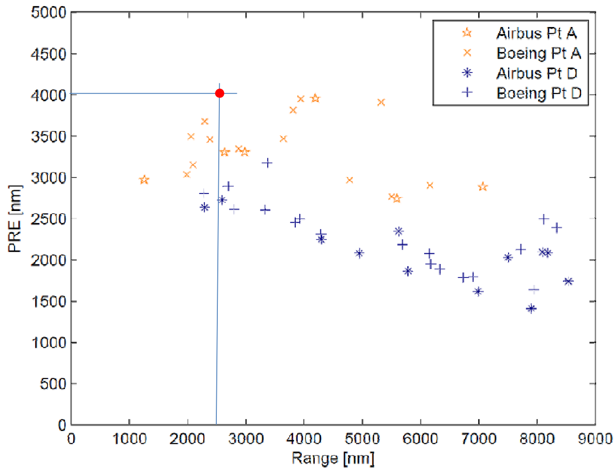

Fig. 5 payload range efficiency comparison between existing aircraft (operated at point A and D) and the cruiser (operated at point D)

The low L/D value (16.2) of the cruiser (notwithstanding its high wing aspect ratio) is reflected in its X factor, which is lower than the values already achieved by new generation long range aircraft (≈15000nm). This is due to two main reasons. First, the configuration of the cruiser generated by the conceptual design tool is far from being optimized and its airfoil shape is extrapolated from an existing aircraft. At the time of writing, an optimization framework is being set up to improve the cruiser wing design. Second, the large fuselage size (with respect to the wing) has a dominant contribution in the total aircraft drag. Hence, the impact on the overall cruiser efficiency by an improved wing design is expected to be lower than for regular aircraft. In a second design iteration, it would be useful to investigate the design of a more slender and/or lift generating fuselage and a fairing system to reduce the fuselage/wing interference drag.

4 Comparative study with direct and staging flight

In order to quantify the fuel saving provided by the AAR operational approach, a comparison study has been performed with direct flight and staging flight. To this purpose the same conceptual design tools employed to size the cruiser have been used to size two other airplanes: one, called D-5k, able to achieve the total range of 5000nm in one stretch, and one, called I-5k, able to achieve the same range by splitting it with one intermediate refueling stop.

The payload (hence the fuselage size), the cruise speed and altitude, the takeoff and landing field length and the engine SFC values were kept the same for the three aircraft. The fuel reservation for the D-5k was computed using the ETOPS regulations. The length of the two cruise legs flown by the I-5k were computed accounting for the part of the mission flown during descend at the end of the first stage and climbing at the beginning of the second stage, in such a way to achieve a total range mission of 500nm.

Fig. 6 provides a comparison of the cruiser and I-5k geometry. As expected, the two aircraft are very similar, not only in shape, as indicated by the percentage differences reported in Table 3. The cruiser does not have the penalty of a second takeoff and climb segment, hence it can achieve a 7% lower fuel mission weight.

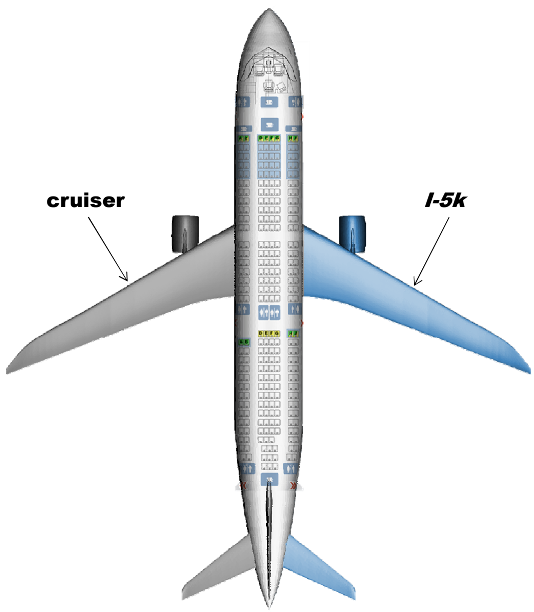

Fig. 6 comparison between the planform of the cruiser and the I-5k aircraft designed for staging flight

OEW	MTOW	Mission Fuel	Engine Thrust	Wing area
-2%	-3%	**-7%**	-4%	-4%

Table 3 percent differences between the cruiser and I-5K performance indicators

The differences in wing, tail and engine size between the cruiser and the D-5k are significant (Fig. 7). The D-5k features the wing/fuselage proportion of a "regular" long/mid-range jetliner and a higher aerodynamic efficiency than the cruiser. However, the higher weight and required thrust make the total mission fuel of the cruiser 20% lower (Table 4).

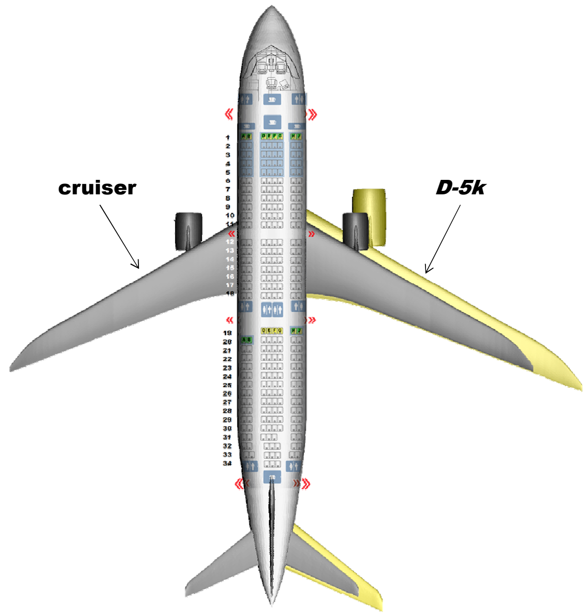

Fig. 7 comparison between the planform of the cruiser and the D-5k aircraft designed for direct flight

OEW	MTOW	Mission Fuel	Engine Thrust	Wing area
-22%	-32%	**-20%**	-32%	-31%

Table 4 percent differences between the cruiser and D-5K performance indicators

In order to estimate the net fuel saving yielded by the AAR operations with respect to direct and staging flight it is necessary to evaluate the amount of fuel burnt by the tanker. This value (hence the tanker refueling efficiency) will depend both on the tanker design and its mission profile. This is addressed in Section 5, where, first, the design of the tankers is briefly discussed and then an estimate of the net fuel saving is provided for different combinations of cruiser and tankers.

4.1 Cruiser vs existing aircraft converted to AAR operations

As elaborated in the previous section, a dedicated cruiser design, developed for a transportation mission of 250pax over a 5000nm range with 1 AAR operation, can provide 20% fuel saving with respect to an aircraft developed for an equivalent direct flight mission. One may ask whether the development of a dedicated cruiser is necessary, or similar savings could be achieved by using existing aircraft. To this purpose, the cruiser presented in the previous section has been compared with two existing aircraft, namely the Boeing B737-800 and B767-300. The first one matches the cruiser in terms of design range (2500nm, hence the range flown by the cruiser before getting refueled in flight); the second in terms of payload capacity. Making use of the data published by the manufacturer and the conceptual aircraft design tools used to design the cruiser, it was possible to obtain the results reported in Table 5.

	Cruiser	B 737-800	Δ	B767-300	Δ
MTOW [kg]	100,865	75,477	-25.1%	147,985	46.7%
OEW [kg]	52,589	38,624	-26.5%	79,028	50.3%
Payload [kg]	26,500	18,587	-29.9%	25,017	-5.6%
Pax	250	186	-25.6%	260	4.0%
Seat Pitch [m]	.85	.76	-10.4%	.80	-5.9%
Mission fuel [kg]	32,929	28,201	-14.3%	51,140	55.3%
X [nm]	14,409	12,855	-10.8%	14,667	0.2%
PRE [nm]	4,024	3,297	-18.1%	2,446	-39.2%

Table 5 comparison of the cruiser with existing aircraft that could be employed for AAR operations

Although the B737-800 has a comparable design range to the cruiser, it is a much smaller, hence lighter, aircraft. Therefore its mission fuel weight is 14% lower, however more than one B737-800 are required to match the capacity of one cruiser. The PRE factor indicates that this aircraft has 18% lower transport efficiency.

B767-300 provides a similar payload capacity to the cruiser: 260 vs. the 250pax of the cruiser, although accommodated in a more cramped seating configuration (about 6% lower seat pitch). However, such an aircraft is designed for a much longer range, hence heavier (double the cruiser OEW), therefore, it would burn about 55% more fuel than the cruiser, once used on the same AAR mission. Its PRE factor is almost 40% lower than the cruiser.

Although the B737-800 and B767-300 fuel weight values used in this comparison are those estimated by the conceptual design tools (based on the MTOW, OEW and payload weight published by the manufacturer), hence subjected to the typical uncertainty of conceptual design tools, it is evident that the development of dedicated cruiser is necessary to obtain benefit from AAR operations.

5 Tanker design and net fuel saving estimation of the AAR operational system

At the beginning of the RECREATE project it was necessary to estimate the impact of the tanker operational radius (in view of selecting suitable airport to host their basis and to account for the effect of the cruiser trajectory on the overall operational concept) and the amount of refueling operations a tanker could perform during the same mission (in view of estimating the size of the tanker fleet and assess the traffic at the tanker bases). Hence, it was decided to design not one tanker but various families of tankers. A first family of tankers was developed for an operational radius of 250nm, each member with the capacity to serve from 1 to 5 cruisers per mission. A second family of tankers was developed for a radius of 500nm, again, able to serve from one to 5 cruisers.

The top level design requirements for the tanker are given in Table 6. The amount of fuel to be transported by these tankers was based on (multiples of) the amount of fuel required by each cruiser to perform its mission (see also Table 2).

During the conceptual design of these tankers, it was decided to investigate both conventional (fuselage and cantilever wing) and joint-wing tanker configurations. Hence, other two families of tankers were developed (250nm and 500nm radius, 1-5 fuel delivery per mission). The generated conventional tanker designs feature a C-tail configuration, to avoid aerodynamic interference between the vertical tail empennage and the deployed boom, as to limit damage in case of accidental detachment of the boom.

Fuel offload per tanker [kg]	14,505
Number of refueled cruisers per mission	1-5
Refueling radius [nm]	250-500
Contact time during refueling [min]	20
Waiting time between refueling [min]	20
Mach @ cruise	0.82
TO&L field Length at sea level [m]	2500

Table 6 tanker top level requirements

The joint-wing tanker configuration was selected in the effort to limit as much as possible the amount of unused space in the fuselage. Reducing the length and the cross section of the fuselage requires larger tailplanes to cope with the combination of large center of gravity excursion and short(er) tail arms. When the tailplane reaches certain dimensions it can be used as back wing to support the main wing structure, hence leading to more compact and lighter tanker configurations.

In view of the higher level of interactivity required to design the tankers and the current inability of the Initiator to deal with non-passenger aircraft and peculiar types of mission such as that of the tanker, AC-X was the selected design tool (see Section 3).

Details of the tanker design can be found in ref. [11]. Fig. 8 shows two of the generated tankers, namely the TC-III-250 and the TJ-III-250: a conventional and a joint-wing tanker, respectively. Both have an operative radius of 250nm and the capacity to serve 3 cruisers per mission. The KC-135 military tanker is shown as well to give a sense of the dimensions of the RECREATE tankers and cruiser. Fig. 8 reports also the weight and the Tanker Efficiency (E_T) factor of the three rankers. E_T is defined as the ratio between the fuel delivered and the fuel used by tanker during its mission.

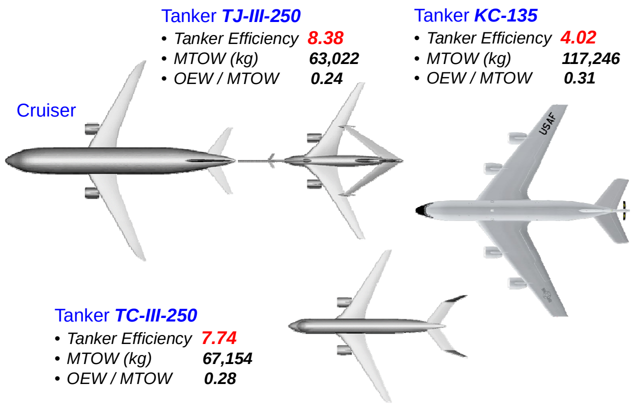

Fig. 8 the cruiser, the TJ-III-250 and the TC-III-250 tankers and the Boeing KC-135 (models are to scale)

Finally, all the tankers of the four families mentioned above have been compared among each other and against the three existing tankers aircraft (The Boeing KC-135, KC-46 and the Airbus A310MRTT), in terms of efficiency and potential fuel saving with respect to direct and staging flight operations, The results for the tankers with operative radius of 250 and 500nm are summarized in Fig. 9 and Fig. 11, respectively. Each data point on the plots represents one tanker. The number of refueling operations that the given tanker is able to provide is indicated on the horizontal axes. The following values can be read on the vertical axes:

- The tanker efficiency values (left). The higher the better, as less fuel is required per unit of delivered fuel.
- The net fuel savings yielded by AAR operations with respect to direct flight (left).
- The net fuel savings yielded by AAR operations with respect to staging flight (right)

The last two percentage values are computed by detracting the fuel used by the tanker from the fuel saved by the cruiser with respect to aircraft operating staging and direct flights (values provided in Table 3 and Table 4, respectively). The horizontal lines on the plots represent the margins, below which the AAR refueling approach cannot competitive with direct and staged flight, in terms of total fuel burnt.

Both figures show that tankers designed for a larger amount of fuel deliveries feature lower efficiency values. This is to be expected, since larger tankers must stay airborne for a longer period, while carrying larger amounts of fuel.

The curves of the existing tankers are based on the actual fuel capacity declared by the manufacturers.

Fig. 9 shows that *all* new tankers designed for the 250nm radius can ensure net fuel savings, with respect to both direct and staging flight operations, even for a number of fuel deliveries as high as 5. In case of tankers able to serve 3 cruisers per mission (Fig. 8), the total amount of fuel used for AAR operations is about 15% lower than for direct flight and 1.5% lower than using staging operations. Higher fuel savings could be obtained by using smaller tankers (2 fuel delivery), at the cost of larger tanker fleets and saturation of tanker bases capacity.

The plot shows also that the use of existing tankers would never allow competing with staging flight operations. The use of the most efficient tanker, the KC-135, would make AAR operations about 10.5% more fuel efficient than direct flight.

It can also be noted that joint-wing tankers are always more advantageous than their conventional opponents.

Fig. 11 shows the comparison between AAR, direct and staging flight operations, when making use of tankers designed for a refueling radius of 500nm.

As expected, all the tanker efficiency values drop, because of the larger distances the tankers have to flight to transport fuel. On top of that, the amount of fuel saving yielded by the cruiser w.r.t. direct and staging flight is also lower, because the cruiser has to be designed for a more stringent fuel reservation strategy. In case of emergency, the cruiser must be able to fly a diversion range twice as large as that indicated in Table 1, which lowers the fuel efficiency of the cruiser and will demand the tankers to deliver larger amount of fuels. Fig. 10 shows the effect of the diversion range on the achievable fuel saving using AAR versus direct flight. Therefore, a new cruiser design was generated to perform the comparative study summarized in Fig. 11. The outcome of this second comparative is that no tanker allows competing with staging flight in terms of fuel savings. Using specifically designed tankers, the

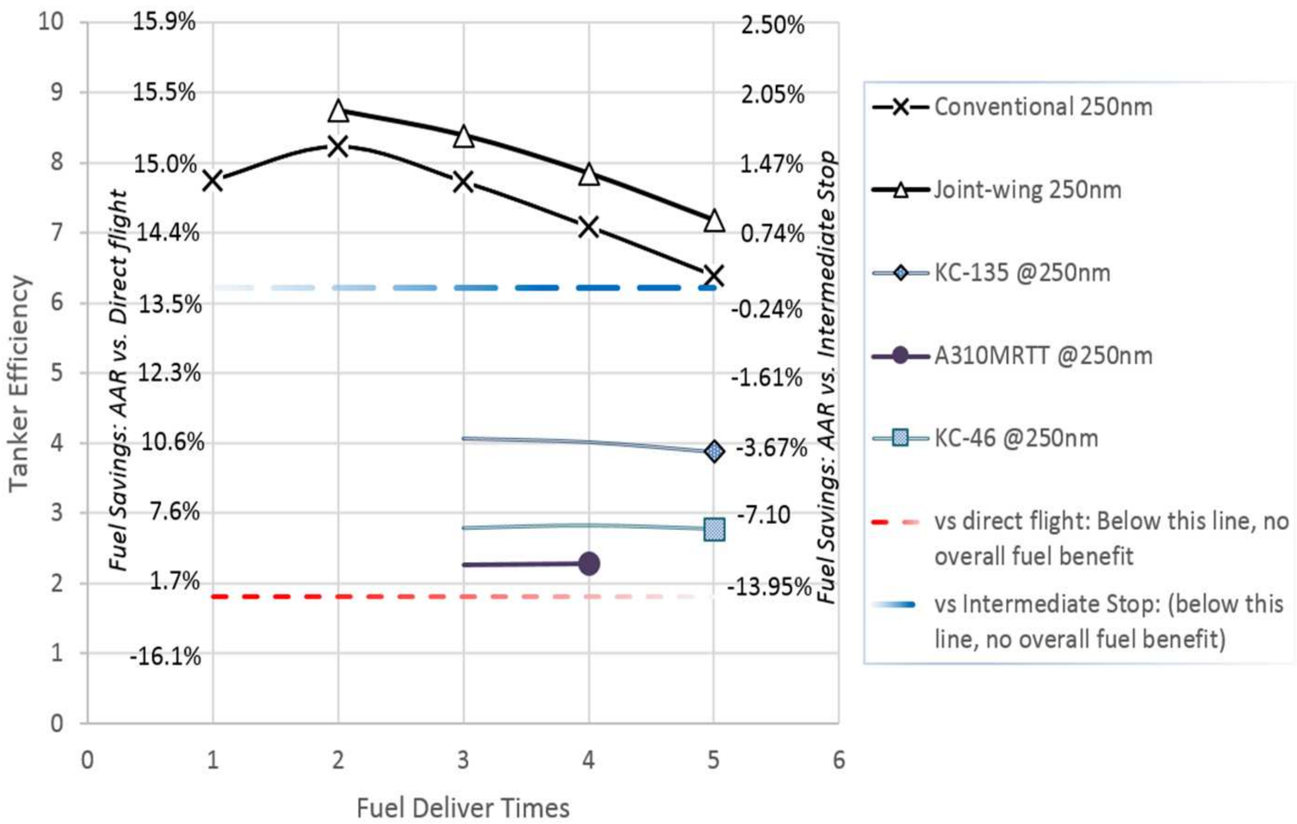

Fig. 9 AAR vs Direct and Staging flight, using tankers with operational radius of 250nm

difference with staging flight fuel consumption is rather small (-1% using joint wing tankers), and a significant 13% fuel savings can still be achieved, with respect to direct flight.

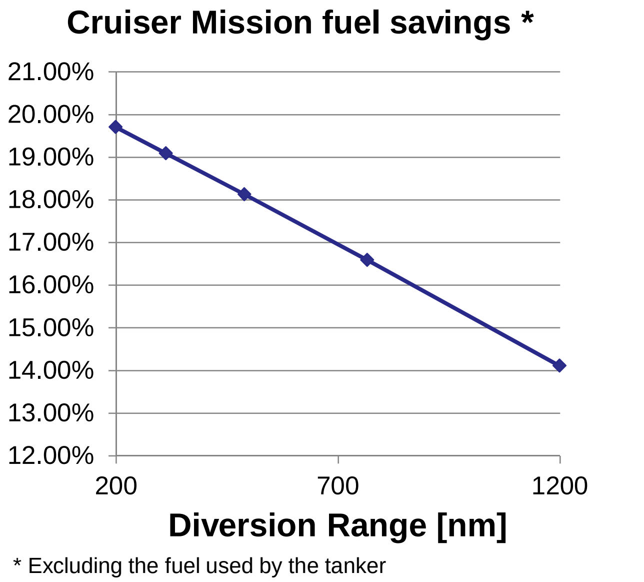

Fig. 10 impact of the diversion range on the achievable fuel savings using AAR vs direct flight

The plot shows also that, even by using the most efficient of the existing tankers, AAR operations would be about 8% less fuel efficient than staging flight and only 6% more efficient than direct flight. This is another proof that specifically designed tankers are necessary to achieve sufficient fuel saving to justify the introduction of AAR operations.

6 Conclusion

This paper discussed the introduction of AAR operations in civil transportation as a means to drastically reduce fuel consumption and related emissions. The design of dedicated cruiser and tanker aircraft, as well as a careful planning of the overall operational system, is necessary to achieve benefits.

This study demonstrates that, the amount of fuel saved by a cruiser to transport 250 passengers over a range of 5000 nm, with one aerial refueling operation, is larger than the fuel burnt by the tankers, yielding a net fuel saving with respect to non-stop and staging flight of 15% and 1.5%, respectively. These savings can be achieved by using joint-wing tankers with an operative radius of 250nm, as far as they do not serve more than 3-4 cruisers per flight. The use of

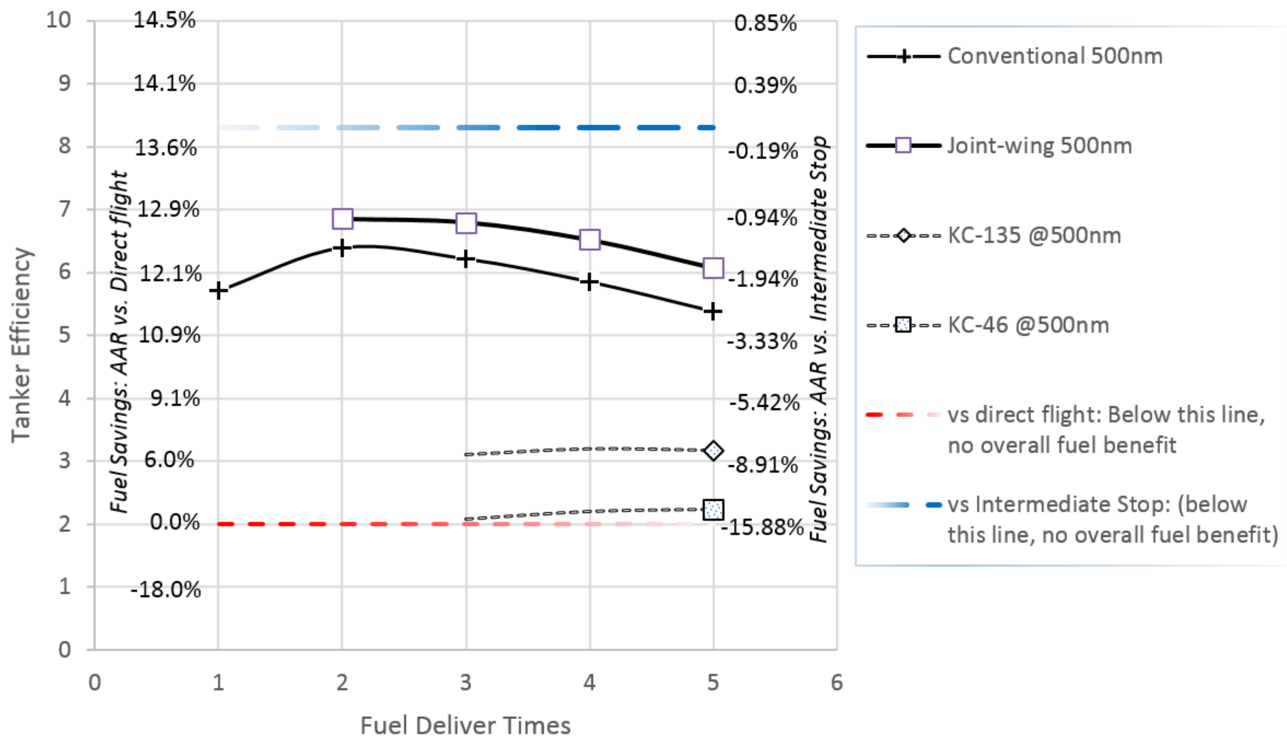

Fig. 11 AAR vs Direct and Staging flight, using tankers with operational radius of 500nm

conventional tanker designs would yield 1% lower fuel savings than with joint-wing tankers.
Although the fuel savings granted by AAR w.r.t. to staging flight seem marginal, it should be considered that AAR has also clear advantages in terms mission duration and aging of the fleet (less air-ground cycles).
Whist this study demonstrated the consistent advantage of using specifically designed cruisers and tankers, it also showed that the use of existing aircraft for AAR operations is always less fuel efficient than staging flight. Using dedicated cruisers and existing tankers, marginal advantages would be yielded w.r.t. to direct flight operations.

Acknowledgement and contact data

The research leading to the results presented in this paper was carried within the project RECREATE (REsearch on a CRuiser Enabled Air Transport Environment) and has received funding from the European Union Seventh Framework Programme under grant agreement no. 284741. This publication reflects only the authors' views. The European Union is not liable for any use that may be made of the information contained therein.
For more information, you can contact the first author at g.larocca@tudelft.nl .

7 References

[1] ACARE. Aeronautics and air transport: Beyond vision 2020 (towards 2050) - *background document*. in, www.acare4europe.com, 2010.
[2] Andrew H. Staging airliner service. in: *7th aiaa atio conf*, American Institute of Aeronautics and Astronautics, Belfast, 2007.
[3] Nangia RK. Operations and aircraft design towards greener civil aviation using air-to-air refuelling. *The Aeronautical Journal*, 110 (2006).
[4] Tyagi A and Crossley WA. Investigating long-range aircraft staging for environment, economic and travel time impacts. in: *9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO)*, 2009.
[5] Langhans S, Linke F, Nolte P and Gollnick V. System analysis for an intermediate stop operations concept on long range routes. *Journal of Aircraft*, 50 (2013) 29-37.
[6] Creemers W and Slingerland R. Impact of intermediate stops on long-range jet-transport design. in: *7th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, 2007.
[7] Timmerman HS and La Rocca G. Feasibility study of a forward extending flying boom for passenger aircraft aerial refuelling. in: *RAS Applied Aerodynamics Conference 2014*, Bristol, 2014.
[8] Timmerman HS and La Rocca G. Conceptual design of a flying boom for air-to-air refueling of passenger aircraft. in: *ICCMSE2014*, Athens, 2014.
[9] La Rocca G, Langen THM and Brouwers YHA. The design and engineering engine. Towards a modular system for collaborative aircraft design. in: *28th Congress of the International Council of the Aeronautical Sciences*, Brisbane, AU, 2012.
[10] Elmendorp RJM, Vos R and La Rocca G. A conceptual design and analysis method for conventional and unconventional airplanes. in: *29th Congress of the International Council of the Aeronautical Sciences*, St. Petersburg, Russia, 2014.
[11] Li M and La Rocca G. Conceptual design of a joint-wing tanker for civil operations. in: *RAS Applied Aerodynamics Conference 2014*, Bristol, 2014.
[12] Tang KG, Rao AG and van Buijtenen JP. Conceptual study of a hybrid turbofan engine with inter turbine burner. in: Engineers ASoM (Ed.) *ASME Turbo Expo: Power for Land, Sea, and Air*, Glasgow, Scotland, 2010, pp. 239-248.
[13] Schmidt KV, R. A semi-analytical weight estimation method for oval fuselages in conventional and novel aircraft. in: *52nd AIAA Aerospace Sciences Meeting*, National Harbor, Maryland, 2014.
[14] Elham A, La Rocca G and van Tooren M. Development and implementation of an advanced, design-sensitive method for wing weight estimation. *Aerospace Science and Technology*, 29 (2013) 100-113.

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