

Overview of the Research on a Cruiser Enabled Air Transport Environment (RECREATE) project

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Abstract

The research reported in this overview paper is all about the introduction and airworthiness of cruiser-feeder concepts of operations for civil aircraft. Cruiser-feeder concepts of operations are investigated as a promising pioneering idea enabling energy efficient air transport of the future. The soundness of cruiser-feeder concepts of operations for civil aircraft has been under investigation in the RECREATE project for 36 months. A concept with fuel transfer from feeder to cruiser, and a concept with payload transfer between feeder aircraft and a nuclear propelled cruiser have been studied extensively. For the latter nuclear cruiser concept, it is concluded that neither airworthiness nor acceptance of the idea by the general public is within sight. However, for the concept with fuel transfer from feeder to cruiser (civil air-to-air refuelling operations), the results of our collaborative research indicate a fuel burn reduction potential on isolated aircraft level between 11% and 23 % for a typical 6000 nautical miles flight with a payload of 250 passengers. It is remarked that the lower bond of this reduction potential is usually considered as large in the aerospace industry. The most important outcome of the RECREATE research is that a clear route has been mapped out on how cruiser-feeder operations (as a concept to reduce fuel burn) could ever comply with airworthiness requirements for civil aircraft. It is proposed to follow an approach similar to certifying for automatic landing systems as specified for All Weather Operations. In line with the corresponding Acceptable Means of Compliance, the performance of the aerial refueling system may be demonstrated through simulations using a model of the system, validated by flight tests. Corner stones of the project for generating all the new data are the optimized cruiser and feeder conceptual and preliminary designs which have been made and refined in two design iterations.

These designs are based on separately formulated airworthy operational concepts. A crucial outcome of the project is the clear vision on the route towards full automation of the whole refuelling phase. Based on the automation concepts chosen and the detailed models created, demonstrations of the performance of the aerial refueling system have been made. The same models have been used in a coupled cruiser – feeder flight simulation experiment involving commercial aviation pilots, to investigate human factors of cruiser-feeder concepts of operations for civil aircraft. From the initial flight simulation experiment, safe refuelling operations are judged as feasible by the pilots involved. Finally, a surprising outcome of the project is the result of the benefits study. Benefits in terms of fuel burn reduction or economic benefits have been studied on an integrated air transport level, accounting for realistic fleet and traffic. Unlike our anticipation at the start of the research, not only fuel burn reduction but also cost reduction seems to be feasible.

Keywords: RECREATE, cruiser-feeder operations, air-to-air refuelling

Nomenclature

AAR	Air-to-air refuelling
AFCS	Automated flight control system
AMC	Acceptable Means of Compliance
AWO	All Weather Operations
CS	Certification Specifications
DIS	Distributed Interactive Simulation
EASA	European Aviation Safety Agency
GECO	Generic Experimental COckpit, DLR research flight simulator
GRACE	Generic Research Aircraft Cockpit Environment, NLR research flight simulator
ICAO	International Civil Aviation Organization
MFW	Maximum fuel weight
MTOW	Maximum take-off weight
OEW	Operating empty weight
RECREATE	Research on a Cruiser Enabled Air Transport Environment

Introduction

Current forecasts estimate a growth above 4% in world-wide air traffic per year for years to come [e.g. 1].

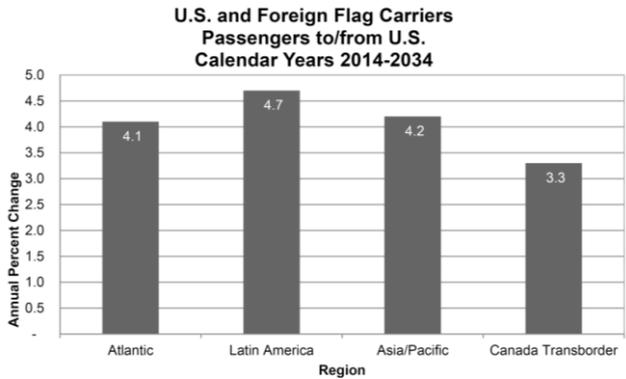


Figure 1: FAA forecast of air traffic development to/from the US [1].

It is widely agreed that an equivalent rise of fuel consumption and CO₂ emissions in aviation will not be acceptable. Current aircraft and propulsion technology developments as well as major step-change contributions to fuel burn reduction are required for the second half of this century. A major step may come from breakthrough technology development or a radical change in operations. One radical change in operations to alleviate the rise in fuel consumption and CO₂ emissions are cruiser-feeder operations.

The definition of the cruiser-feeder concept states that the payload - passengers and/or cargo - are transported for the largest part of the way by one transport aircraft, called the cruiser. During flight, a mid-air contact with another aircraft is initiated. This second aircraft, the feeder, either joins the cruiser physically for a large part of the journey, or couples for a limited time to exchange passenger, cargo and/or fuel. Such a contact can take place one or several times during one journey. An obvious special case of cruiser-feeder operations, air-to-air refuelling (AAR), has been studied in the past. Estimations of the attainable reduction in fuel burn was shown in research by [2, 3]. These estimations suggested further in-depth research to underpin the data with refined analysis.

The European Union 7th Framework Programme funded project REsearch on a CRuiser Enabled Air Transport Environment (RECREATE) is conducted by nine European research institutes, universities and small business partners [4]. In 42 months, the feasibility of cruiser-feeder operation concepts is studied, aiming at assessing the implications of a re-creation of air transport operations. The overarching objective of the RECREATE project is to demonstrate, on a preliminary design level, that cruiser-feeder operations substantially reduce fuel consumption and CO₂ emissions, and can be shown to ever become airworthy. The multi-disciplinary collaborative research is organised as an evolutionary delivery team effort, with several iterations of each

activity, and the results of each iteration being fed into the following iteration of all other activities. The research has been organized along three integrating activities (1-3) and three in-depth, more technical activities (4-6), each of them with their own objectives. Below, the activities are addressed including their outcome to-date.

1) Concepts for cruiser-feeder operations

The objective of this integrating activity is to develop, iterate, select and describe two cruiser-feeder concepts, for further study. One chosen concept is realizable in the distant future (at least 50+ years from now), the other concept however is expected to be realizable in the medium-term (within 20+ years from now). This concept requires development and acceptance of new airworthiness regulations, but can be done with today’s technology.

First, a conventional baseline without cruiser-feeder operation is defined to compare the benefits of future concepts with today’s technology, see Table 1 [5]:

Table 1: Baseline concept

Cruiser	
Capacity	250 passengers
Range	6000 nm
Specific fuel consumption	0.525

Given the broad definition of cruiser-feeder operations, iterations conducted at the start of this activity involved a large diverging number of cruiser-feeder concepts. In a subsequent convergence sweep, two concepts were down selected for further investigation [5]. The first final concept is civil air-to-air refuelling, of which the overall characteristics are shown in Table 2:

Table 2: First final concept: Air-to-air refuelling as special case of cruiser-feeder operations

Cruiser		Feeder	
Capacity	250 passengers	Fuel offload capacity	35000 lb / 3 contacts
Range	2500-3000 nm	Range / endurance	500 nm / ~4 hours
MTOW	100000 kg	AAR envelope	< 24000 ft, Mach < 0.8
Specific fuel consumption	0.525	AAR procedure	20 min (5 min wet contact)

Concepts with transfer of payload and passengers based on engines burning chemical fuel have been shown not to be economically feasible, as the overall weight of the system and thus the total amount of fuel burnt are too high. However, if the cruiser can be

propelled by a nuclear power source, the efficiency is very high compared to the reference case, even if the total weight of the system is higher. Although the nuclear cruiser cannot be shown to meet airworthiness requirements with today’s technology, this concept has been retained for study because it cannot be excluded that new nuclear physics will be discovered and confirmed in the future. The second final concept (Table 3) concerns a nuclear propelled cruiser where the transfer of passengers and cargo is done via a life supporting container mechanism.

Table 3: Second final concept: cruiser-feeder with nuclear propelled cruiser

Cruiser	
Capacity	1000 passengers
MTOW	900000 kg
Range / endurance	60000 nm / 1 week
Cruise speed	M = 0.8
Docking speed	M = 0.7
Cruise altitude	> 36000 ft
Payload transfer	Single container station concept (100 passengers each)

Extensive air transport traffic simulations have been conducted for the AAR concept [6]. The effect of geographical constraints on cruiser-feeder operations has been addressed in these simulations. Two different scenarios are studied, the transatlantic case and the Europe-Asia case. As already expected from the baseline operations, benefits of cruiser-feeder operations are affected by geographical constraints such as for instance the location of tanker bases.

A serious attempt has been made to account for the effect of relocation of traffic, and the effect on the traditional hubs and spoke system. Finally, a study into operational constraints due to weather, i.e. turbulence, pointed out the geographical areas, flight altitudes and times of the year with the least chances of turbulence. Current operational forecasts tend to over-forecast turbulence occurrence. New and improved methods to forecast and observe turbulence will most likely further lower the false alarm rate while maintaining the correct positive forecast rate [6].

2) Airworthiness

The objective of this integrating activity is to develop a route towards airworthiness of cruiser-feeder operations. Bringing two aircraft in close vicinity of one another in mid-air, either for docking or for refuelling, is potentially dangerous. Today, no civil certification regulations concerning cruiser-feeder

operations exist. However, the airworthiness of such a concept must be established along the guidelines of the current regulatory system of the safety of civil aircraft operation and with an equivalent level of safety.

Based on the concepts of operations described, a Functional Hazard and System Safety Analysis of the selected cruiser-feeder concepts is performed to map all hazards not covered by current airworthiness regulations, for both cruiser-feeder concepts [7]. For all identified hazards mitigation actions or design solutions have been proposed. A system safety model is developed to quantitatively show the requirements for an airworthy and reliable cruiser-feeder operation.

Finally, an approach for the certification of airworthiness of civil cruiser-feeder operations is being developed taking into account existing military regulations for aerial refuelling. An evaluation of the existing EASA Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes (CS-25 Amendment 11) has been made, resulting in an overview of applicable specifications and specifications to be amended for cruiser-feeder operations [8]. Following the evaluation, an approach to certification has been proposed. Because of their similarity of operations this approach has been based on the regulations covering automated landing, the EASA CS-AWO (All Weather Operations) [9]. The similarity lies in the objective to achieve an accurate and safe approach to a specific position. The amended regulations and Acceptable Means of Compliance (CS-AWO AMC) cover the required safety level, the considered conditions regarding aircraft, operations and environment, the performance requirements, performance demonstration and failure conditions.

Simulations will be used to get quantified data for these models, for normal operation and for the most critical scenarios:

- For wind shear or turbulence encounter the most critical situation is the station keeping position with the boom almost connected or just disconnected (boom very close to cruiser) and a sudden upward movement of the cruiser.
- For system failures the most critical situation is the station keeping position and a sudden engine failure, with or without the boom almost connected or just disconnected.

It has to be noted that real ground and flight testing to demonstrate the safe operation of nuclear propulsion is not justifiable due to the inherent risk of the release of radioactivity. Here, the development of high fidel-

ity simulation with a very high level of confidence far beyond the current state-of-the-art is required.

3) Benefits:

The objective of this integrating activity is to analyse economic benefits, dispatch reliability and environmental effects of cruiser-feeder operations using the defined baseline as reference. The impact on fuel consumption, exhaust emissions, local noise production and shareholder value are studied. In the remaining six months of the project the final benefit analysis will be made [10].

Benefits analyses of the updated concept indicate a range of fuel and mass savings for the cruiser aircraft for cruiser-feeder concepts in which only fuel is transferred (Fig. 2). Remark that it is a challenge for an optimized conventional configuration cruiser to be as efficient as an aircraft optimized for long range, because of the relatively larger fuselage and fixed weight of some of the equipment, furnishings etc. On the conservative side, fuel savings for the cruiser only - derived bottom-up by aircraft design - amount to around 21% for one refuelling. With two refuellings, this value could be increased, and further investigations on the effect of thrust-to-weight ratio and reserve fuel are ongoing. From this benefit the fuel consumed by the tanker(s) has to be subtracted. If the tanker is very efficient with a fuel ratio - i.e. ratio fuel given / fuel consumed - equal to 8, the tanker reduces the total efficiency of the cruiser-feeder combination by about 5-6%. In case of a more realistic tanker with a fuel ratio of 4, the impact of the tanker is a reduction by about 10-12%. A lower bond of fuel saving is in the order of 11%, which is still a huge fuel saving compared to nowadays standards in the industry. On the optimistic side and based on a top-down, statistical approach, an upper bond of 23% fuel saving for the cruiser-feeder combination has been calculated previously.

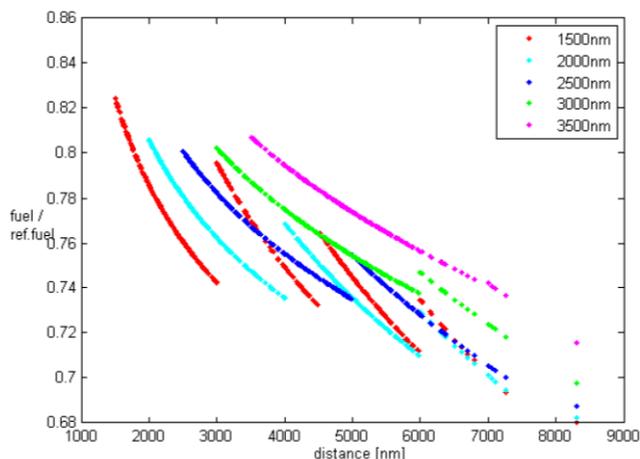


Figure 2: Fuel savings for single cruiser routes and different cruiser design ranges [10]

Traffic simulations are used to assess the benefits on fleet and network level. Based on these analyses and for a specific historic mix of aircraft and traffic, obtaining a reduction of total operating cost of 14% was found possible [11]. This result shows that an economical benefit can be achieved for the carrier, i.e. not only a reduction of fuel cost but an overall beneficial way of operation in spite of very high investment costs. This result was not anticipated at the start of the RECREATE project.

The environmental impact next to the reduction of fuel burn and thus CO₂ emissions has been studied as well. A consequence of smaller and lighter cruiser aircraft compared to today’s long range passenger aircraft is a reduction of noise at the departure/arrival and hub airports, which are mostly located in densely populated areas. A noise reduction in turn leads to economic benefits through reduced noise fees and a rise in property value near existing airports. The noise impact through the additional heavy load near the required tanker bases has not been investigated. The tanker bases are assumed to be located in sparsely populated areas, where noise is not of a great influence.

AAR has been shown to be beneficial in terms of fuel reduction compared to non-AAR, even when considering a network based on more point-to-point connections, less on a hub-and-spoke system [12]. Implementing AAR on a large scale will thus also enable more long-range point-to-point services and thus lead traffic away from existing hub airports and towards regional airports, with the related economic and environmental consequences.

4) Aircraft design:

The objective of this activity is to conduct conceptual and preliminary design iterations of dedicated cruiser and feeder aircraft according to the chosen concepts. Families of cruiser and feeder aircraft are generated as well as refuelling boom designs. The generated design data is used in support of the benefits analyses, the airworthiness analyses and the automatic flight control system development [13].

Cruiser and feeder aircraft specifically designed and optimised for their task have been shown to increase the benefits achievable by air-to-air refuelling. The gain results on the one hand from the fact that a long-range cruiser aircraft designed for a specific range including refuelling will have a reduced Operating Empty Weight (OEW) as it will be designed for a smaller Maximum Fuel Weight (MFW) and thus a smaller Maximum Take-Off Weight (MTOW). Design studies of long-range passenger aircraft able of

being refuelled have been performed with conceptual and preliminary design tools.

On the other hand, also the tanker design has a huge impact on the overall efficiency. Current military tankers, however, are not optimized for the refuelling task but are converted cargo and passenger aircraft. Dedicated tanker design studies have shown the advantages of a joint-wing tanker concept [14].

A trade-off study showed that a non-conventional, inverted receiver-tanker configuration is beneficial and essentially the more viable configuration (Fig. 3). Such a configuration increases the safety of the passenger aircraft from possible debris from the tanker or refuelling boom after a collision, removes possible passenger discomfort due to flying in the tanker wake and limits the amount of extra pilot training required to the much smaller number of tanker pilots. Furthermore, the passenger aircraft need a minimum of refurbishment for the new manoeuvres, and thus have a minimum loss of cruise efficiency, while the costly surplus thrust requirements and supporting equipment lay with the smaller number of tankers.

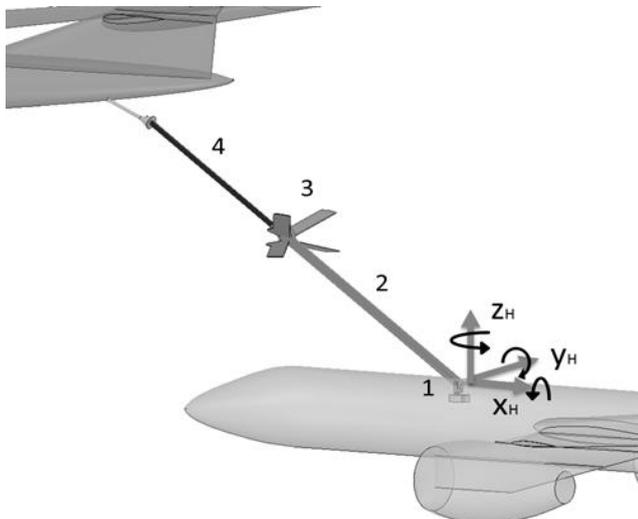


Figure 3: Forward extending boom concept. Receiving passenger aircraft up and left [15]

A number of different concepts for a forward extending boom have been studied by [15]. A big challenge lies in the controllability and aeroelastic stability for this concept. Preliminary aeroelastic analysis results show that a design space free from static and dynamic aeroelastic instabilities exists [16].

Preliminary design with aerodynamic CFD computations for a refuelling boom for the conventional configuration has been done by [17]. An aerodynamic database was created containing the results of about 800 computations for a number of relative boom position parameters and the control surfaces' de-

flexion angles. This preliminary aircraft design data supports the development of an automated flight control system.

Several design studies by the Technical University of Delft have investigated the nuclear cruiser concept in cooperation with the Nuclear Research and Consultancy Group NRG [13, 18]. A pressurized container exchange concept was adopted for the in-flight transfer of passengers, crew, cargo and consumables, see Fig. 4.

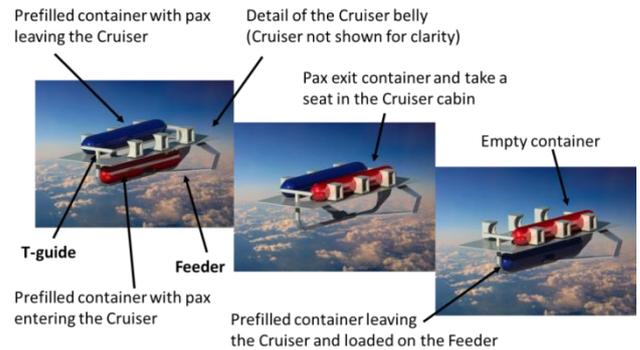


Figure 4: Container exchange concept for passenger and cargo transfer [13]

On a conceptual basis, weight estimations, aerodynamic design and design of a nuclear propulsion system for the cruiser aircraft were performed; see Fig. 5 for a conceptual design sketch. Options for a Brayton cycle and a Rankine cycle propulsion system were studied.

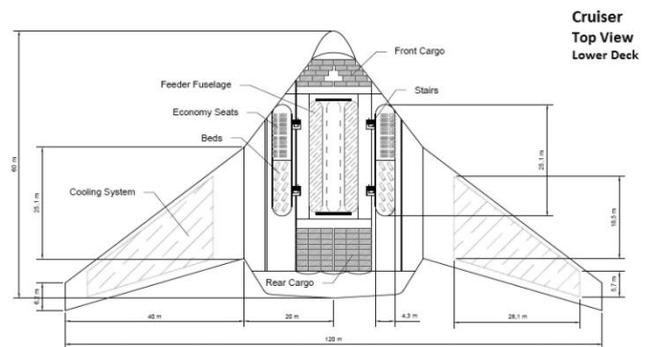


Figure 5: Conceptual design of a nuclear cruiser aircraft [13]

The research for a feasible design of a nuclear propelled aircraft is ongoing.

5) Automated flight control system:

An early assessment showed that successful cruiser-feeder operations will require the development of automatic flight control systems for the cruiser aircraft, the feeder aircraft and the refuelling boom. The objective of this activity is to conceive this automated in-flight refuelling system, including redundant sensors, actuators and controllers, and to model that

system in a realistic simulation environment. Automation is a prerequisite in order to comply with the imposed safety and reliability requirements [19]. Based on simulation results, the feasibility of civil air-to-air refuelling can be investigated, also for conditions with specified levels of turbulence.

The development of the automated flight control systems has been based on the conventional AAR configuration due to the maturity of this concept. The complete transfer process has been defined and the required components have been identified. The estimation of the relative position between the aircraft is modelled using four independent measurement technologies with current performances of accuracy. The relative position between the boom tip and the receptacle is estimated using the aircraft relative positions and an additional optical sensor system. The data is shared between the two aircraft by data link.

Controllers have been developed for the cruiser aircraft, the tanker aircraft and the aerodynamically controlled refuelling boom. As additional safety measure, the manual abort by the pilots of either aircraft has been introduced. The design has been successfully tested in closed-loop simulations for moderate turbulence levels involving two large civil transport aircraft as cruiser and tanker aircraft [20]. Figure 6 gives an example of such a closed-loop simulation.



Figure 6: Closed-loop simulation of the approaching, rendezvous and station keeping phases [19]

Currently, stochastic simulations are being performed for these models to show the safety of these manoeuvres for extreme conditions of small probabilities. This approach will also allow to identify potential weak points in the design.

6) Flight simulation:

The objective of this activity is to, firstly, verify the developed models and flight control systems in flight simulator experiments. Secondly, the impact of the human-machine interface and contributing human factors, such as pilot workload, on the safe and re-

liable execution of the refuelling manoeuvres are assessed by professional airline pilots [21].

Two research flight simulators have been adapted to conduct these civil air-to-air refuelling manoeuvres. The developed simulation models and the automatic flight control systems [19] were integrated in the real-time simulation environments of the research flight simulators at NLR and DLR, GRACE (Generic Research Aircraft Cockpit Environment) respectively GECO (Generic Experimental Cockpit).

A Human-Machine-Interface (HMI), which consists of the information displays and control mechanisms available to the pilots in the cockpit, has been developed (Fig. 7).



Figure 7: Human-Machine Interface for refuelling manoeuvres in the System Display [21]

During the experiments these two flight simulators were run in a coupled mode, the tanker aircraft being modelled in GECO and the cruiser aircraft in GRACE. The required connection of several host computers in two countries was made via internet using a so-called Distributed Interactive Simulation connection (DIS).

The experiments are split in two phases, the first of which has been conducted by four crews of professional pilots from two major European airlines in 2013. This first phase of experiments focussed on the evaluation of the nominal procedures of all manoeuvre phases, and also included a forced abort manoeuvre due to a too high approach speed.

The evaluation is based on the feedback by the pilots on the cruiser-feeder concept as a whole, the operational procedure, the Human-Machine Interface and recommendations for improvement. All pilots who flew the experiments reported that they had the impression that air-to-air refuelling of civil aircraft, can be performed within present day safety levels with such a highly automated flight control system. They also indicated that the proposed air-to-air refuelling manoeuvre does not require specific additional skills from the pilots [21].

With the results of the successful first phase of simulator sessions, the operational concept and the developed flight control and monitoring systems will be improved. For example, additional and improved information on the refuelling process will be offered to the pilots in the cockpit. In a second phase of simulator sessions later in 2014, more complex manoeuvres, including non-nominal and emergency conditions, will be evaluated.

Conclusions and Outlook

Starting out with the earlier assessments of the benefits of cruiser-feeder operations which had pointed out the aerial refuelling concept as a promising concept, the RECREATE project has been able to show in a consolidated, congruent way that civil air-to-air refuelling can be implemented in an airworthy and economically and ecologically beneficial way. A number of research methodologies coming from different fields and institutes were employed to cover the basic questions about the feasibility of what could be a complete renewal of the existing air transport system.

Due to the complexity of analysing a whole transport system and based on the choices and assumptions made for a comparison, only a range for the change in fuel reduction can be given. The conservative, aircraft-design driven and bottom-up derivation amounts to 11% fuel reduction, including also the fuel used by the tanker aircraft. The statistical, top-down specification shows an upper range of 23% fuel reduction. Implementing AAR on a large scale will enable more long-range point-to-point services and thus lead traffic away from existing hub airports and towards regional airports. This in turn also leads to local economic consequences.

From a design point of view, the conventional military refuelling configuration would be replaced by a forward-swept boom configuration which has been shown to be the most promising option, for safety, economical and passenger comfort reasons.

Future research required for making civil AAR a reality should include the conception of realistic business cases for air transport organisations, aircraft fuel providers and other stakeholders. Regarding airworthiness, the development of a roadmap for civil certification regulations in consultation with certifying authorities is envisaged. Technical research should focus on the design of automated flight control systems and on the airworthiness of the forward

swept boom configuration, including ground and flight test demonstrations.

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