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A HOLISTIC APPROACH TO HYPERSONIC AIRCRAFT DESIGN: ZEHST (ZERO EMISSION HIGH SPEED TECHNOLOGIES)

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Abstract

Shortening passenger travel time is a key focus for future long-range air transportation, as is meeting the air transport industry's ambitious environmental goals. Targeting these objectives, the ZEHST program was set-up with the ambition to address the design of a hypersonic transport aircraft with a holistic approach, and to use at best the technical and industrial expertise of the partners involved: Airbus Group, Airbus Defense and Space, ONERA and MBDA.

Fig. 1: Artist view of ZEHST

1 General Introduction: Project Background

1.1 History and High-Level Requirements

The ZEHST program was born in the frame of the French-Japanese cooperation. An initial ZEHST study, based on the Astrium Spaceplane project, first allowed the derivation of high level requirements for the vehicle:

- Long range flights (typically Paris-Tokyo or Tokyo-Los Angeles) in less than 3 hours
- Between 50 and 100 passengers
- Operations from a standard airport
- Standard level of comfort for untrained passengers
- Reduced environmental impact
- Entry into Service (EIS) as early as possible, targeted for 2025

1.2 The Hypersonic Transport DNA

By essence, a high speed passenger transport is a new product at the crossroads between existing subsonic airliners, supersonic aircraft and manned space vehicles.

From subsonic passenger transport, it inherits the passenger and cabin aspects, the airworthiness regulations including noise and emissions, the flight and ground operations (Air Traffic Management (ATM), airport compatibility) and the subsonic aerodynamics for its take-off and landing phases.

From the low supersonic aircraft (Mach<2), it inherits the supersonic airbreathing propulsion, involving complex inlets and nozzles, and the supersonic aerodynamics, including the sonic boom impacts.

Finally, from the spacecraft, it inherits the thermal loading resulting from high speeds, the high altitude environment (including radiations) and the design and operating procedures associated to cryogenic fuels (including tanks).

In the specific case of ZEHST, the initial vehicle was constructed by hybridizing the Astrium Spaceplane (itself a hybrid between a subsonic airplane and a rocket) with the addition of a high speed airbreathing propulsion (a ramjet).
To drive successfully the 2-year project co-funded by the French Direction Generale de l'Aviation Civile (DGAC), Airbus Group Innovations (AGI) decided to gather in the ZEHST consortium key partners with expertise in space (Airbus Defense and Space, then Astrium), high speed air breathing propulsion (MBDA) and subsonic and supersonic aircraft (ONERA, Cassidian and Aeroconseil).

2 Design Approach

The specificity of the ZEHST program is to approach hypersonic transport design with a holistic view. In addition to the traditional hypersonic conceptual design focused on propulsion, aerodynamics and materials, all aspects of the vehicle life-cycle, from concept to certification and down to airline operations are considered, in order to build a credible and realistic vehicle.

The rationale for this choice is to reduce the risks associated with such a radically new concept by allowing a full exploration of the design field; covering not only the vehicle key design parameters but, beyond this, all of its operating and regulatory key factors.

To minimize the development risks and costs and to be on the market as soon as possible, it was decided to select as a starting point a well-defined Spaceplane baseline rather than a blank sheet of paper. Furthermore, the choice was made to use whenever possible mature existing components or high Technology Readiness Level (TRL) components being developed for other applications, thus benefiting from cross-product synergies.

3 Achievements

In a holistic approach, the commercial and operational requirements studied during the ZEHST project will be presented first, followed by its regulatory framework, and finally by the end design resulting from this environment.

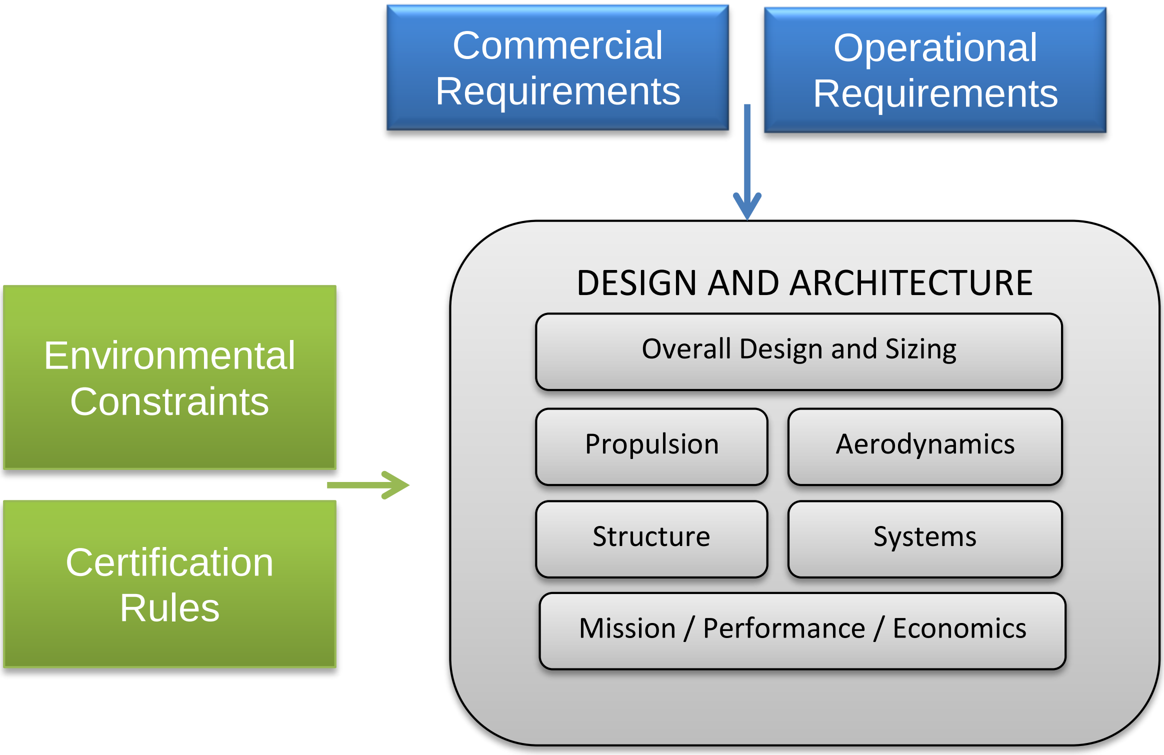

Fig. 2: ZEHST Design Approach and Disciplines

3.1 Commercial and Operational Requirements

3.1.1 Market Analysis

The time gain provided by a high-speed transport over subsonic aircraft only becomes significant (and thus valuable to the passenger) when the cruise phase of the flight is long enough. The ZEHST vehicle is thus aiming at long range segments over 2000nm.

Fig. 3: Overview of the ZEHST Routes

For all origin-destination city pairs above this threshold and up to the maximum range of the vehicle (~5500nm), the volume of premium passengers is evaluated at the horizon 2030. Assuming a given market share for high-speed transport, the traffic on each route is computed so as to eventually select ~40 airports meeting the traffic, environment and connectivity criteria for ZEHST. The overall number of aircraft required to operate this network is estimated to be between 100 and 200.

But beyond the pure time saving, the great advantage of high-speed transport for long-haul travel is to enable a return trip in the same day. This allows the business traveler to return home in the evening and skip all jet-lag related discomfort. Smart scheduling to accommodate the time zone shift between origin and destination enables this one day return trip concept. This service would thus open a new era in long-haul travel, provided it comes with fast transport concepts to and from the airport, and inside the terminal. The paradigm brought by this service, together with the possible shift from business jet travelers to ZEHST should increase the high-speed market share previously estimated.

3.1.2 Operations

Today's applications of high-speed propulsion technologies (rocket engine and ramjet) are mostly expendable. Adapting the design of these engines to sustain a high number of flight cycles (including in-flight restart) is a key challenge for the design.

The number of flight cycles per item (especially on the propulsion side) is thus a key trade-off between technical feasibility and cost efficiency. At vehicle level, achieving the highest number of flight cycles per year is desirable for economic efficiency, but should comply with realistic inspection and maintenance constraints.

To enable the one day return trip with the simplest logistics, the assumption of 1 daily return trip (i.e. 2 flights) per aircraft is made.

The constraints imposed by current airports pavement loading and runway length are considered for the design to be compliant with today's infrastructure on the airside (runways and taxiways). On the terminal area, some more flexibility is assumed (especially in the vehicle length), considering that a vehicle equipped with cryogenic fuels, and with hot skin surfaces at arrival would anyway require dedicated gates, which would also enable express passenger service.

At this conceptual design phase, the detailed maintenance procedures were not defined. However, some preliminary accessibility volumes were allocated to enable maintenance operations on engines.

3.1.3 Passenger Experience

Moving from high subsonic speeds (M 0.85) to high supersonic (M 4.0) should bring the same paradigm in the passenger experience as when the first jets replaced turboprop aircraft on long-range flights. Then, trip time was drastically cut and beds were replaced by reclining seats.

Tomorrow, high-speed long range travel should feel very close to short/medium haul flights of today. With a flight duration of 3 hours and a return trip in a day, the cabin design and service will be optimized for efficiency. The seats should be simply reclining and the overhead bins should accommodate the carry-on items required for a single day stay. Similarly the layout should allow the quickest possible boarding and de-boarding times. The current design, with two slender cabins, each located in an over-wing pod, is favorable. With 2 seats abreast, each passenger should benefit from aisle access, and with only 30 passengers per pod, passenger should be very quickly in and out of the cabin. Furthermore, VIP procedures at the airport should allow a service "straight to the aircraft" to reduce the overall journey time.

Fig. 4: Inside View of the ZEHST Cabin

The overall noise levels in the cabin were investigated, and especially those generated from the high-speed propulsion types (rocket engine). Both airborne and structure-borne noises were looked at and the appropriate insulation means were implemented, both between the cabin lining and the pods' external shell, and between the pod itself and the wing structure.

To ensure passenger comfort, on top of the noise insulation, much care is taken to limit the overall acceleration to an acceptable level of 1.15g, so that untrained passenger can travel ZEHST with a comparable comfort level to subsonic aircraft.

Finally, the effects of natural cosmic radiation on passengers and crew are studied at the flying altitude of ZEHST (~25km). The analysis conducted showed that the levels received by pilots flying 4 weekly flights (12.3 mSv/year) are compliant with today's regulation for professionals (20 mSv/year). For passengers, the frequency of exposure should be less, and thus the radiation is less critical. In the event of a solar flare, however, the level of radiation will increase. Flight crew should thus not be exposed to more than 3 solar flares a year.

3.2 Regulatory Environment

3.2.1 Impact on the Environment

Naturally one remembers that Concorde was not allowed to fly supersonic over populated areas due to sonic boom induced noise levels on ground. But choosing over-water routes can only be considered a default solution, and future certification rules will most probably be even more stringent. Therefore more innovative solutions will be required.

Mitigating the sonic boom can be partly performed by shaping the trajectory so as to minimize the impact on ground of the sonic boom signature, which mostly depends on the aircraft mass and external shape. Computations have been performed to assess N-shape waves. Future efforts to reduce the magnitude of the boom will include reducing the vehicle mass, optimizing its aerodynamic shape and adjusting its altitude together.

The noise from the rocket engine is also investigated. Its impact on ground is a function of the climb angle during the ascent phase as well as the altitude at which the engine is started. Using aero-acoustic models, it is then possible to determine noise levels on a typical flight and further adjust the trajectory so that high noise does not occur above populated areas. This is illustrated in the following figure, which shows the actual noise signature on a typical Paris-Tokyo flight, at different points in an ascending trajectory. The noise levels not considered acceptable, marked red, should be restricted to non-populated areas.

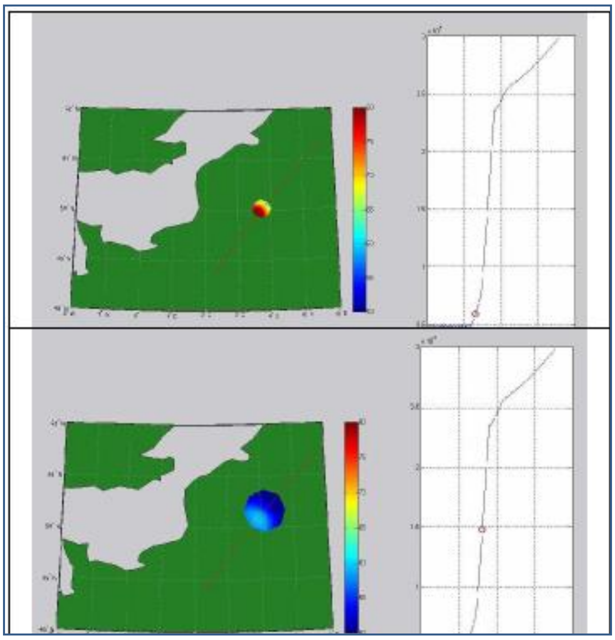

Fig. 5: Examples of Noise Footprint during Ascent with Rocket Engines

Regarding emissions, hydrogen propelled aircraft like ZEHST produce two main exhaust gases: water vapor and NOx (Nitrogen Oxide). To contain NOx production, a smart arrangement of the injectors in the combustion chamber allows the reduction of high temperature zones to reach NOx levels comparable to conventional subsonic engines.
On the water vapor side however, the combustion of hydrogen generates about 3 times as much water vapor (75g/MJ) per unit energy as kerosene (29g/MJ). This is all the more detrimental since the life duration of water vapor in the atmosphere is expected to increase with altitude, which would increase its radiative forcing. However, with the size of the fleet being relatively reduced, its overall global warming impact should be assessed.

3.2.2 Certification

Although it is too early to talk about the certification of a future hypersonic civil aircraft, basic principles should be taken into account as early as possible. Whether derived from an existing certification basis or rebuilt for this new aircraft type (like for Concorde), the certification document should review the risks, be those directly transposed from subsonic rules, not applicable for high supersonic applications or totally new. The means of compliance and design solutions to cope with these risks should be addressed jointly with the design team, to avoid over constraining the design and impeding its feasibility.

A simple counter-example on ZEHST is the Uncontained Engine Rotor Failure case (UERF) where an a priori means of compliance is to separate both turbofan engines from a given distance, thus positioning each of them on a wing, at the back of each pod. This led to a dual pod design, with an induced performance penalty. In a second iteration of the design, one could consider other means of compliance that are less penalizing to the vehicle performance. Furthermore, and even at early stages, one should consider a consistent level of safety requirements between already certified equipment (i.e. turbofan engines) and not yet certified equipment (i.e. ramjets).

3.3 Design and Architecture

3.3.1 System Engineering - Overall Design and Sizing

The initial requirement of an early entry into service drove the choice towards existing propulsion types, each operated sequentially in its optimal speed regime: turbofan engines for take-off and landing, rocket engines to cross the transonic regime as quickly as possible and ramjets for cruise around Mach 4. Hydrogen is the fuel selected for cruise and bio-fuel is preferred for turbofans to use “off-the-shelf” engines.

The overall sizing of the vehicle is then performed using a multidisciplinary optimization (MDO) process based on reduced models for each discipline (aerodynamics, propulsion, masses etc…). The design is optimized to meet the range target at minimum total fuel burn.

From that onwards, iterative system loops are performed to determine a reference concept, taking into account systems and sub-systems definition and integration, especially propulsion, landing gear, fuel tanks, etc.

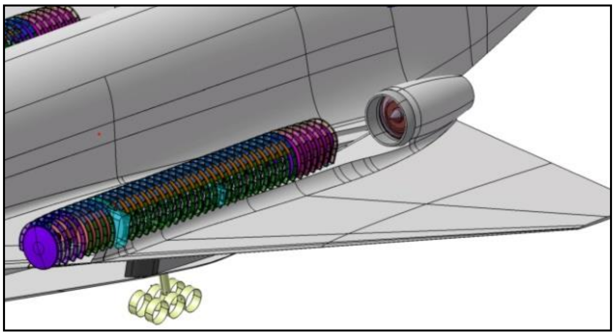

Fig. 6: External View: the ZEHST Wing and Pod

3.3.2 Mission Analysis, Performance and Economics

The flight profile is adjusted to minimize fuel consumption. After take-off with the turbofans, rocket engines are ignited at mid altitude, to cross the transonic regime and reach a point (Mach, pressure, altitude) that allows the ramjets to be started. Once in the cruise phase, at an altitude of around 25 km, only the ramjets are in use. Cruise is followed by a gliding descent until starting conditions for the turbofans are met (at around 10km), which then remain in operation until landing. Some steep climb scenarios were investigated in order to minimize the sonic boom impact on ground, however the penalty induced on range was too high and so they were finally not selected.

On the target mission, the fuel burn is computed per passenger, which then allows a Direct Operating Costs to be assessed.

3.3.3 Propulsion and Fuel System

Each propulsive system (turbojet, ramjet, rocket engine) has to be studied and precisely defined, including fuel tanks management.

Ramjet technology can be considered proven for unmanned applications up to Mach 5, using kerosene fuel. In the case of ZEHST of course, further development will be necessary to have a hydrogen-fueled ramjet compatible with future aviation certification rules (including for instance the torching flame case). The ZEHST design work on the ramjet is mostly focused on developing a geometry with the most versatile range of operations (from Mach 1.5 to 4.0) while still remaining compact and with limited mobile parts.

The rocket engines for the ZEHST project are derived from the types used in the Ariane commercial launch vehicle and the Spaceplane, using cryogenic hydrogen as fuel and cryogenic oxygen as an oxidizer, stored in dedicated tanks. Here again the engines should demonstrate compliance with a future certification, and the ability to perform multiple cycles. The experience of a previous program (e.g. Spaceplane) could definitely help in this respect. The oxygen tank is pressurized with helium, and is located at the back of the vehicle, close to the rocket engines. The large hydrogen tanks, located in the main fuselage, should maintain auto-pressurization thanks to the boil-off of the hydrogen. The tank insulation should be adjusted to optimize this boil-off effect. In order to assess the tank loads and the vehicle center of gravity, simulation of the fuel motion in the tanks during key manoeuvers is performed. In a further study, the detailed need for anti-sloshing devices will be considered.

3.3.4 Aerodynamics

To refine the aerodynamic database used in the MDO, some CFD analysis is performed over the Mach range. At low speed, much emphasis is made on the inlet flow of the turbofan engine, to make sure that the ingestion of the pods' boundary layer will not generate too much distortion on the engine, and that flow separation at high angle of incidence will not surge the engines. Furthermore, the impact of the pod on the wing vortices is investigated.

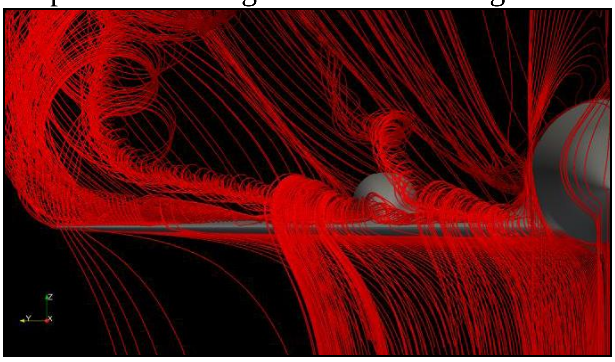

Fig. 7: Wing Vortex Visualization under Low-speed High-angle of Attack Conditions

At supersonic speed, the CFD analyses are dedicated to shock interactions between the fuselage, the pods and the wings to confirm the overall cruise performance.

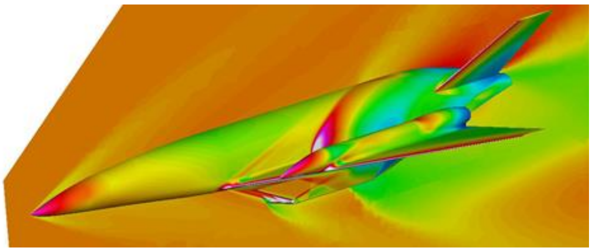

Fig. 8: Flowfield around the ZEHST vehicle in cruise conditions (Mach in the symmetry plane and Pressure on the vehicle surface)

3.3.5 Materials and Structural Design

The challenge is to find lightweight materials capable of resisting high stress levels and temperatures (up to 600°C) over a large number of consecutive flight cycles.

A database of possible materials was created. The selected material is the Rene 41, a nickel based alloy.

A preliminary structural design is performed relying on conventional design principles inherited from existing aircraft.

3.3.6 Thermal and Energy Management

Thermal management is of course a difficult task to tackle due to the wide range of temperatures between cryogenic fuels (-250°C) and high-temperature leading edges (600°C). This requires high efficiency thermal insulation to adequately control the boil-off in the tanks, and reduce thermal stress on the structure, whilst remaining lightweight and durable.

On the opportunity side, thermal energy can be considered a potential source to power the onboard systems.

3.3.7 Systems and Avionics

Some conceptual studies are performed to integrate the main aircraft systems, including the integration of the landing gear with the aircraft body and the preliminary architecture of the flight controls.

The human factors are also taken into consideration, especially for the cockpit positioned in one of the pods. Some synthetic vision is considered for the pilot to provide a more centered view from the aircraft, and also to have a runway view during landing without the need for a droop nose.

4 Lessons Learned and Way Forward

4.1 Lessons Learned

The ZEHST initial study conducted under the DGAC contract showed the technical feasibility of such an aircraft, capable of carrying 60 passengers over a transcontinental range in 3 hours. However, the stringent requirements imposed at the beginning of the project, for instance EIS in 2025, led to a sub-optimal design. In this first status, the design needs to increase its robustness to bear the uncertainties of a program development without risking divergence towards an infinitesimal payload vehicle. This design thus requires more work to secure the robustness of its economic competitiveness.

In a second iteration of the design, one should consider integrating more advanced technologies in order to reach better performance and environmental levels (lower mass, lower fuel burn, lower noise and emissions). This implies relaxing some of the requirements, for example postponing the EIS towards 2040 or 2050, and developing new technologies and more integrated vehicle architectures (especially from the propulsion perspective).

4.2 Roadmaps and Partnerships

In order to conduct the maturation of these new technologies in a coordinated and consistent manner, some roadmaps were initially developed within the ZEHST project, including the various technology development steps as well as the progressive integration of these new technologies into ground benches and flight demonstrators.

To consolidate and make these roadmaps converge at European and Japanese levels, Airbus Group Innovations is now leading a consortium of 12 European and 4 Japanese partners in the HIKARI project. The 2-year HIKARI project (for High speed Key technologies for future Air transport - Research and Innovation cooperation scheme) should deliver a joint Euro-Japanese view on high-speed technology roadmaps and flight experimentation.

Likewise, the HEXAFLY-INT project aims at gathering expertise and resources from several continents to enable a joint flight demonstration.

4.3 Other Applications and Spin-off

Pursuing such an ambitious goal as high-speed air transport means permanently challenging today’s boundaries and extending the field of mastered technologies. This process of technology acquisition will not only benefit this particular aircraft but should result in fruitful applications to other fields and products, as what happened during the development of Concorde.

These spin-offs may appear in many disciplines. For instance, the investigations on new propulsion concepts will foster research on alternative fuels such as hydrogen and methane, and therefore pave the way to their mass production and operational use, to the benefit of both subsonic aviation and automotive. Likewise, research on resilient materials can bring enhanced performance to high temperature components of subsonic aircraft, such as combustors or turbine blades. From an energy efficiency standpoint, the work on thermal energy harvesting could also benefit conventional aircraft. Finally, from the environment perspective, the studies done on the water vapor impact on the stratosphere could also apply to the polar flights of today’s airliners.

5 Conclusion

From the design perspective, the holistic approach selected for the design of the ZEHST hypersonic transport clearly demonstrates the value of this method to explore the uncharted territories of such a radical and ambitious project. As the boundaries, constraints and sizing cases may be completely different from those of a well-known design, it is crucial to explore the whole design space, not only in terms of vehicle sizing, but also of operating environment in a wider sense (including certification and environment), in order to gain a sound understanding of the problem and to identify the key drivers of the design.

Specifically, the environmental study in ZEHST has allowed discovering unexpected boundaries, showing that if burning hydrogen only produces water vapor, the greenhouse effect of this water might very well be higher than the one of CO2 at high altitudes. Likewise, the preliminary safety analysis has highlighted that some new scenarios are potentially extremely critical, like the failure of the thermal management system, or the rapid cabin decompression at high altitude.

A holistic approach is thus essential to understand the true design drivers of such a radical design and explicitly highlight the challenges and the design levers to tackle them.

From the program perspective, the ZEHST study has led to some major achievements.

First, the technical feasibility of such an aircraft, capable of carrying 60 passengers over a transcontinental range in 3 hours is shown, with an overall design close to today's accepted airport limits.

Second, some important lessons on consistency are derived. First on certification, where requirements consistency is necessary between existing components (e.g. turbofan) and future components (e.g. ramjet) in order to achieve a balanced design. Then on the TRLs to control the uncertainty at product level and guarantee a stable and robust design.

Third, it is essential to push technologies beyond their current boundaries to achieve an acceptable payload fraction, which is a pre-requisite to the aircraft's competitiveness.

To reduce the risks and split the development costs associated with such ambitious technologies, the development efforts should be shared. First, with other technology applications that are synergetic, such as alternative fuels with the automotive industry. Second, between international partners, in order to secure strong support from each country's industry and their respective governing bodies. Joint initiatives are already emerging in this direction, especially the HIKARI project which aims to bring closer together the hypersonic visions being developed in both Europe and Japan. Further efforts of this kind should be encouraged on the path towards large-scale flight demonstrations.

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