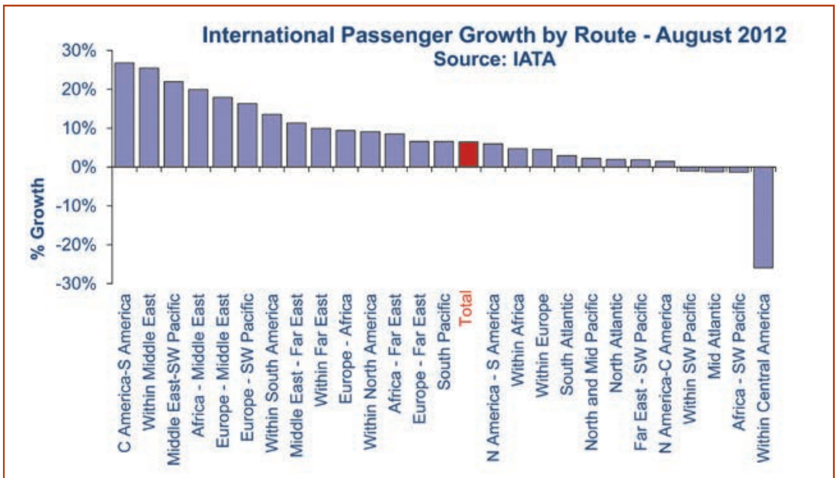
Travelling the Skies at High Speed

Obviously, high-speed air travel only pays off for long distance travels. Though Concorde, flying at Mach 2, still made sense for exploitation along the transatlantic routes, higher speed vehicles should essentially be exploited along longer routes up to antipodal destinations. Then, a typical journey from Stuttgart to Sydney would last about 4 hours when travelling at a cruise speed of Mach 5 or beyond.



01

International passenger Growth by Route [8].

1. Introduction

Tendencies in aeronautics clearly show a steadily increasing market share in premium long-haul flights which classically cover the international and intercontinental routes **(01)**. Based on IATA statistics of August 2012, total international travel is still increasing for the premium and economy traffic growth respectively with 8.5% and 6.2% higher than a year ago in August 2011. In particular travel from Europe to the South-West Pacific, Far East and Middle East grew fast than the average rate and some of them at a double digit pace.

ABSTRACT

Pioneering the aviation for the second half of the century is a theme which is closely followed by ESA in terms of civil high-speed air transport applications. The experience and know-how in high-speed aerodynamics acquired through numerous re-entry missions and high-speed propulsion units from future re-usable launchers are important elements to bridge the gap between classical aerospace and aeronautics. This overlapping area of interest allows bringing in competences from both areas to establish this pioneering vision. Several activities were already initiated by ESA in the field of hypersonic cruisers, i.e. LAPCAT and ATLLAS or to suborbital flights, i.e. FLACON and FAST20XX. These projects are co-funded by the EC and a large group of about 30 different partners from industries, SMEs, research institutions and academia. Though these activities are mainly technology driven programs, the specifications and requirements for the research and development are driven by conceptual studies on hypersonic and suborbital vehicles. Different hypersonic cruiser concepts have been devised so far for different cruise velocities ranging from Mach 3 to 8 while maximizing the range. Antipodal ranges such as Brussels to Sydney seem feasible but more detailed studies are now required along with flight experiments.

Classically, these long-distance flights take easily flight times of 16 hours or more to connect two major intercontinental cities. They become more attractive when travel-time would be reduced drastically such that a final destination can be reached within 4 hours or less. However, with present aircraft and propulsion designs, we're getting close to the optimal design and margins for further improvement are getting smaller. Only drastic changes in aircraft configuration, propulsion concepts and flight velocities are able to achieve these goals.

Sticking to the usual cruise speeds at Mach 0.9 (i.e. 950km/hr), new aircraft configurations and propulsion units presently studied are looking into e.g. blended wing-body configurations and high bypass turbofans mounted on the leeside of the airplane **(02)**. These interesting developments will decrease further fuel consumption up to 30%, however, the will not enable the shortening of travel times.

New aircraft development seems to be stalled with respect to flight speed, despite the proven technical possibility shown by the supersonic Concorde, the experience gained in military aircraft design up to Mach 3 (e.g. SR-71) and finally experimental vehicles (e.g. X-15 at Mach 6). Opponents to supersonic transport development always point to the large specific fuel consumption of Concorde which undeniable is roughly twice the value of present commercial aircraft. However, one should not forget that the specific fuel consumption, sfc, obtained for the first turbojet driven aircraft, e.g. Comet in 1951 were only 20% lower. Since then, fuel consumption reduction for aero-engines has been drastically driven throughout time by specific technology developments e.g. cooling techniques, new alloys, improved thermodynamic cycles by increased pressure ratios and TIT, etc… As the Olympus 593 engine was based on the Olympus design of 1950 for the Canberra and later for the Avro Vulcan in 1956, it is hence impossible to compare its sfc with e.g. the latest Trent's of R&R or the GE90-family when half a century of technology development has not been implemented in these Olympus engines.

2. Motivation and Assessment

As mentioned above, reducing travel times by going supersonic makes only sense on long-distance flights. Range is hence an important figure of merit to evaluate high-speed aircraft concepts. It is strongly dependent on total available fuel mass and its consumption throughout the itinerary, i.e. from taxiing, speed-up cruise and final descent manoeuvres. Among these different parts, cruise represents a major portion of the needed fuel. The range achieved during cruise can be easily derived from the Bréguet range equation:

$$R = \frac{H}{g}\eta\frac{L}{D}\ln\left[\frac{1}{1-W_F/W}\right] = \frac{V_\infty}{g\ sfc}\frac{L}{D}\ln\left[\frac{1}{1-W_F/W}\right]$$

02

Blended Wing Body design: future optimization potential for subsonic airplanes (Credits: NASA).

where:

R Range [m]

H the fuel energy content [J/kg]: 120 (LHV) and 142 (HHV) MJ/kg for H_2, 43.5 (LHV) and 47MJ/kg (HHV) for kerosene, 50.0 (LHV) and 55.5MJ/kg (HHV) for Methane

g gravity constant [m/s^2]

η the overall installed engine efficiency

sfc specific fuel consumption [kg/s/N]

V flight velocity [m/s]

W total take-off mass [kg]

W_F fuel mass [kg]

The range depends linearly on the energy content H in the fuel which can be increased with a factor of 2.7 by switching e.g. from kerosene to hydrogen.

The aerodynamic performance given by L/D in eq. (1) depends primarily on the Mach number and was analysed by Küchemann [9] who formulated a general empirical relationship referred to as the “L/D barrier”:

$$\left(\frac{L}{D}\right)_{\max} = \frac{4(M_\infty + 3)}{M_\infty}$$

Further studies optimized waverider designs taken into account viscous effects resulted in better L/D ratio resulting in a shifted L/D barrier (Anderson [10]).

$$\left(\frac{L}{D}\right)_{\max,\, viscous} = \frac{6(M_\infty + 2)}{M_\infty}$$

For an increasing Mach range the values are decreasing asymptotically to a value of 5 or 7: **(T1)**

This decrease of aerodynamic performance with increasing Mach number would inherently exclude long-range supersonic flight as it would be economically not viable. However, the overall propulsion efficiency, defined as

$$\eta = \frac{T \cdot V_\infty}{m_f' \, H} = \frac{V_\infty}{sfc \;H}$$

increases with Mach number for turbojets and ramjets as will be explained further. A first approach, suggested by R.G. Thorne according to [9] is given by:

$$\eta = \frac{M_0}{M_0 + 3}$$

To better understand the increase of the overall efficiency η of an aircraft engine, one can split the term thermodynamically into a thermal and propulsion efficiency $\eta = \eta_t \, \eta_p$ given approximately for a single jet by:

$$\eta_t = \frac{m'(V_j^2 - V_\infty^2)}{2m_f' H} \qquad \eta_p = \frac{2V_\infty}{V_j + V_\infty}$$

The thermal efficiency of either compressor or ram-based engines can be approached as a Brayton cycle and hence its efficiency is mainly driven by the combustor temperature T_{cc} to intake temperature T_a ratio. This ratio would be at its optimal point when operating the combustor close to the stoichiometric value. However, for turbojets or turbofans, the rotary turbine components limit this ratio due to material yield strengths to a value of about T_{cc}/T_a=6 or η_t = 47%.

Typical values for propulsion efficiency of a modern engine at M_∞=0.85 is 48% for a turbojet and 77% for a turbofan with a bypass ratio of 6. The overall efficiency in cruise results into values of 20% to 37% and increases above 40% for larger bypass ratios [11].

For ram- and scramjets, the combustion temperature is not limited by rotary components. Hence higher equivalence ratios are easier to reach and ER=1 (i.e. stoichiometric) is presently used in scramjet flight experiments. Hence, the thermal efficiency can reach values as high as η_t = 60-70%. The propulsion efficiency is clearly better as the jet/flight velocity difference is typically smaller resulting into a η_p = 70-90% leading to an overall efficiency of η = 42-63%. This large η_p implies however that a massive intake needs to be foreseen, which can occupy the complete frontal section of

M_∞	0.9	2	4	6	8	10
$L/D_{max,euler}$	17.3	10	7	6	5.5	5.2
$L/D_{max,viscous}$	19.2	12	9	8	7.5	7.2
η	0.25	0.4	0.57	0.67	0.73	0.77

T1

Table: Aerodynamic L/D barrier and overall installed engine efficiency in function of flight Mach number.

the aircraft in order to provide the necessary thrust given by $T = m'(V_j - U_\infty)$.

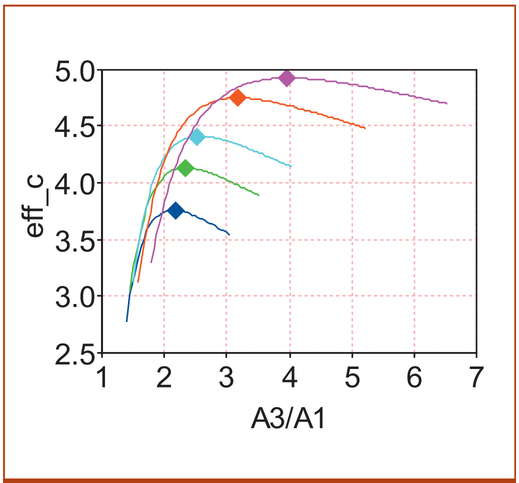
As shown above, both factors η and L/D have reverse dependencies on flight Mach number and for a first assessment the cruise efficiency $\eta L/D$ can be considered in first order to be constant, i.e. a value of about 3 to 4, at worst only 40% smaller for careful designs. This means that the range is theoretically more or less independent of the flight speed and is then only determined by the relative fuel fraction W_F/W and the fuel type. To achieve this goal practically is not trivial, i.e. technical implementation where both propulsion and aerodynamic efficiencies can be harmonized without negative mutual interference requires a dedicated approach. Classical approaches rely on separate and dedicated optimization design routes with respect to aerodynamic and propulsion. A multi-disciplinary approach is actually needed where both the propulsion engineer and the aerodynamicist work closely together to reach for a global optimization.

As this is not a trivial work methodology, it is not so surprising that high-speed transportation has been hampered by the lack of range potential or a too high fuel consumption stemming from a too low cruise efficiency. Indeed, looking into the performance of classically designed high-speed vehicles, their performances drop nearly linearly with flight Mach number as indicated by the red line on **(04)**. Over the last years, however, radical new vehicle concepts were proposed and conceived having a strong potential to alter this trend. This innovative approach is based upon a well elaborated integration of a highly efficient propulsion unit with a high-lifting vehicle concept. The realization of both a high propulsive and aerodynamic efficiency is based upon the minimization of kinetic jet losses while striving to the best uniformity but minimal induced velocity for lift creation.

An optimization analysis integrating both the aerodynamics and the propulsion unit on a two-dimensional conceptual design showed a potential cruise efficiency factor $\eta\ L/D$ beyond 4 for flight Mach numbers above 3.5 **(03)**. This means that the range is more or less independent of the flight speed and is then only determined by the relative fuel fraction W_F/W or the structural efficiency.

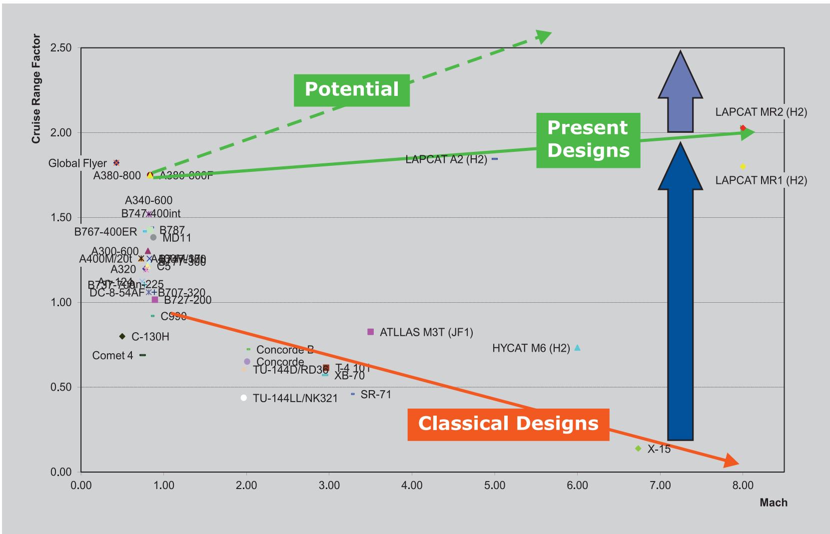
The dashed green line in **(04)** illustrates the potential of this innovative design methodology whereas the green line indicates what has been achieved as a revolutionary, high speed civil air transportation concepts worked-out along this new approach.

At present, the promised performances can only be demonstrated by numerical simulations or partly experimentally. As high-speed tunnels are intrinsically limited in size or test duration, it is nearly impossible to fit even modest vehicle platform completely into a tunnel **(05)**. Therefore experiments are limited either to the internal propulsive flowpath with combustion but without the presence of high-lifting surfaces, or to complete small-scaled aero-models but without the presence of a combusting propulsion unit. Though numerical simulations are less restrictive in geometrical size, they struggle however with accumulated uncertainties in their modelling of turbulence, chemistry and combustion making complete Nose-to-Tail predictions doubtful without in-flight validation. As a consequence, the obtained technology developments are now limited to a technology readiness level of TRL=4 (components validated in laboratory).



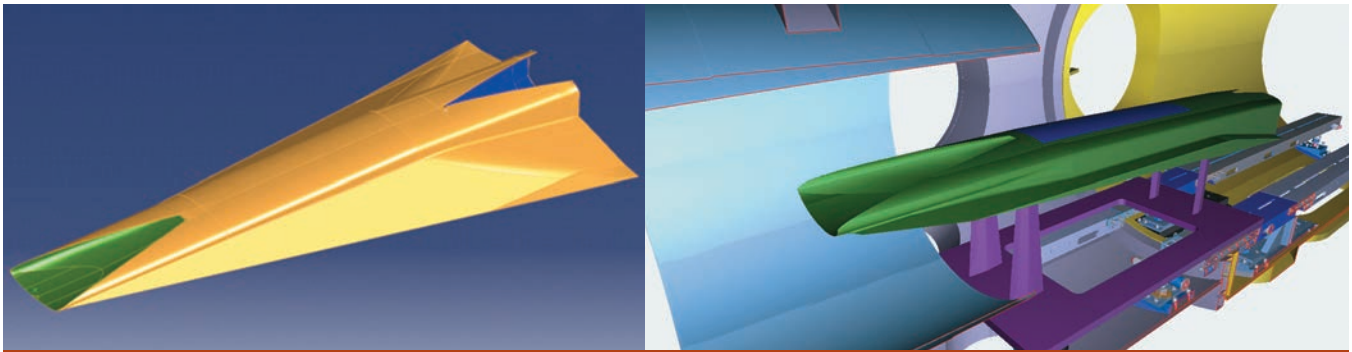
03

Cruise efficiency as a function of A3/A1 (nozzle/air capture area ratio) for Mach numbers between 3 (blue) to 5 (pink) in steps of M=0.5 [5].



04

Long-range potential of high-speed vehicles in function of flight Mach number: Red: achievable with classical designs with minimal integration; Green: present designs based upon strongly integrated propulsion-vehicle designs with a potential limit (dashed line).



05

Left: example of a completely integrated vehicle concept with intake (green), nozzle (blue) and fuselage-wings (gold), Right (courtesy of DLR): corresponding internal flowpath model maximized within tunnel without aero-planform (1.5m long).

Performing a test flight will be the only and ultimate proof to demonstrate the technical feasibility of these new promising high-speed concepts versus their potential in range and cruise. This would result into a major breakthrough in high-speed flight and create a new era of conceptual vehicle designs.

3. High-speed cruisers

These promising feasibility results as well as the remaining open questions with respect to variable engine cycles, materials, engine-airframe integration, thermal protection etc… justify the need for more in-depth studies and analyses related to these disciplines. The LAPCAT project (Long-Term Advanced Propulsion Concepts and Technologies) has been set up to focus mainly on technologies related to engines and their integration into the airframe [1][5]. Material, structures and thermal protection technologies are addressed within ATLLAS (Aero-Thermodynamic Loads on Lightweight Advanced Structures) [3][6]. Both projects incorporate preliminary designs of supersonic and hypersonic cruisers with flight Mach numbers ranging from Mach 3 to 8. Detailed discussions and related references about the different vehicle concepts including the revisiting of American concepts can be found in [2][3]. Here, only the presently retained European vehicle concepts are highlighted.

A conceptually optimized Mach 3 flight vehicle was configured in ATLLAS which allows countering the known lift drop at high speeds by expanding the engine exhaust over an as wide area as possible. The analysis indicated that venting the exhaust in the lee of the wing and base of the fuselage may enable a supersonic aircraft with cruise efficiency competitive with their subsonic rivals, whilst offering significant potential to reduce sonic boom. A vehicle configuration has been developed featuring a circular fuselage with nose intake and an internal high bypass turbofan **(06)**. Exhaust is ducted to the wing and fuselage bases. The wing has a high aspect ratio for good subsonic performance while drag due to thickness is eliminated by exhausting approximately two thirds of the propulsive stream from the wing trailing edge.

Another design approach maximized rather the thermodynamic engine efficiency by exploiting the liquid hydrogen fuel on board as lowest sink temperature (20K) in the cycle. The hydrogen powered LAPCAT A2 vehicle flying at Mach 5 indicated that a 400 ton, 300 passenger vehicle could achieve antipodal range. The concept is particularly interesting for these mission requirements as a trajectory optimization allowed to fly almost continuously over sea and avoiding sonic boom impact when flying over land.

The proposed aircraft configuration A2 is shown in **(03)**. The vehicle consists of a slender fuselage with a delta wing carrying 4 engine nacelles positioned at roughly mid length. The vehicle is controlled by active fore-planes in pitch, an all moving fin in yaw and ailerons in roll. This configuration is designed to have good supersonic and subsonic lift/drag ratio and acceptable low speed handling qualities for take-off and landing.

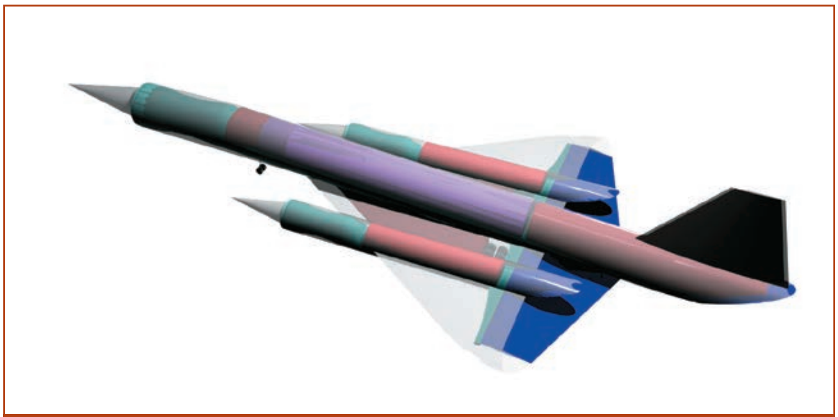
The conceptual designs for a Mach 8 civil transport aircraft within LAPCAT II are all based upon dual mode ramjet to achieve these high cruise speeds. Still, as shown in **(08)**, these preliminary design processes resulted so far in three quite different concepts: a TBCC design from ONERA/ULB/UNIROMA based on the PREPHA re-usable launch vehicle [13][17], an axi-symmetric design from MBDA combining RB- & TBCC [14], and a TBCC based wave-rider concept from ESA-ESTEC [15][16]. So far, the waverider concept has been put forward for an extensive ground-testing phase.

The large database resulting from the ground tests and nose-to-tail computations for the different configurations shall finally result into the definition of a flight configuration. Meanwhile, a feasibility study, called HEXAFLY [18] has been initiated to assess different options of flight testing. The project aims to achieve a first maturation and a proof of concept to experimentally fly-test these radically new conceptual designs accompanied with several breakthrough technologies on board of a high-speed vehicle. This approach would increase drastically the Technology Readiness Level (TRL) up to 6 (System demonstrated in relevant environment).

The emerging technologies and breakthrough methodologies strongly depending on experimental flight testing at high speed can be grouped around the 6 major axes of HEXAFLY:

1. *High-Speed Vehicle Concepts* to assess the overall vehicle performance in terms of cruise-efficiency, range potential, aero-propulsive balance, aero-thermal-structural integration, etc...
2. *High-Speed Aerodynamics* to assess e.g. compressibility effects on transition, aerodynamic vehicle shapes with high L/D, stability, etc…
3. *High-Speed Propulsion* to evaluate the performances of high-speed propulsive devices such as intakes, air-breathing engines (ABE), nozzles (SERN) including phenomena such as high-speed combustion, injection-mixing processes, etc…
4. *High-Temperature Materials and Structures* to flight test under realistic conditions high temperature lightweight materials, active/passive cooling concepts, reusability aspects in terms oxidation, fatigue, etc…
5. *High-Speed Flight Control* requiring real-time testing of GNC (Guidance Navigation Control) in combination with HMS/FDI technologies (Health Monitoring Systems/Fault Detection and Isolation)
6. *High-Speed Environmental Impact* focusing on reduction techniques for sonic boom and sensitivities of high-altitude emissions of H_20, CO_2, NO_x on the stratosphere.

To mature this experimental flight testing, a scientific mission profile will be defined followed by a proof-of-concept based upon:

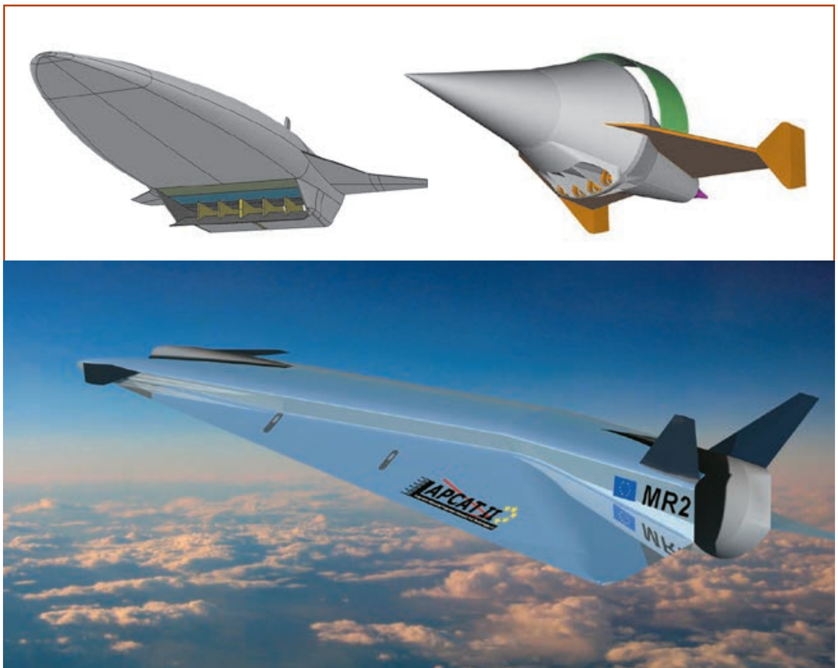


06

M3 Configuration with fuselage and wing skins off (GDL) [12]. Cyan: air flow path; blue: wing nozzle and thrust surfaces; red: fuel tanks; magenta: cabin.

07

LAPCAT A2 (REL): Mach 5 hydrogen based vehicle (top) with precooled turbofan-ramjet Scimitar engine.



08

Layouts of 3 remaining Mach 8 vehicle concepts: PREPHA derived vehicle from ONERA, Univ. of Brussels and Rome (top left), axi-symmetric design from MBDA (top right) and waverider based design from ESA-ESTEC (bottom).

- a preliminary design of a high-speed experimental flight vehicle covering the 6 major axes
- selection and integration of the ground-tested technologies developed within LAPCAT I & II, ATLLAS I & II , FAST20XX and other national programs
- identification of the most promising flight platform(s)
- allowing to address following items:
- identification of potential technological barriers to be covered in a follow-up project
- assessment of the overall ROM-costs to work the project out in a follow-up project
- the progress and potential of technology development at a higher TRL.

The vehicle design will be the main driver and challenge in this project. The prime objectives of this experimental high-speed cruise vehicle shall aim for

- an integrated conceptual design demonstrating a combined propulsive and aerodynamic efficiency
- a positive aero-propulsive balance at a cruise Mach number of 7 to 8 in a controlled way
- making optimal use of advanced high-temperature materials and/or structures
- an evaluation of the sonic boom impact by deploying dedicated ground measurement equipment.

4. Critical technologies

Apart from providing the characteristics and claimed performances of these vehicles, also the required technologies to achieve these goals are gradually developed including the constraints imposed by the environmental impact. The technologies address specific needs of:

- advanced combined engine cycles able to operate over a wide speed range;
- the characterization of high-temperature light-weight metallic, composite and ceramic materials;
- active and passive cooling systems for internal and external thermally loaded components;
- different storable and cryogenic fuel types;
- multi-disciplinary and multi-physics optimization tools and
- finally the need of experimental campaigns at real flight conditions for validation with respect to high-speed aerodynamics and combustion, designed by existing European ground test facilities and state-of-the-art multi-dimensional and multi-physics numerical models.

The environmental issues entail not only the emissions of CO_2 or NO_x but also the effect of contrails, sonic boom and impacts on the stratosphere. Preliminary results indicate the feasibility of achieving fuel consumption and emission rates reaching nearly the same level as conventional aircrafts.

5. Conclusions

Hypersonic technology developments within an European context have been revisited theoretically and on the basis of on-going EC projects LAPCAT and ATLLAS. Both projects are complementary addressing the required technology development allowing for hypersonic aircraft design and manufacturing i.e. aerothermodynamics, combustion, metallic and composite materials, conceptual vehicle design, numerical tool development and validation…

These projects aquire the needed knowledge and technologies for a complete vehicle design and to test and evaluate them experimentally and numerically. The aim is to verify the feasibility of the concept to perform a complete mission including acceleration and cruise. In parallel, the environmental impact in terms of NO_x generation, ozone depletion, sonic boom… are considered.

Preliminary concepts for Mach 3.5 and M4.5 demonstrated the possibility to cover a distance beyond 10,000km based on kerosene. Switching to hydrogen allows extending this distance provided careful attention is given to the propulsion cycle, the aerodynamics and the propulsion-airframe integration. The particular Scimitar cycle mounted onto the LAPCAT A2 makes an antipodal flight possible at Mach 5 flight speed. Going beyond this speed has shown so far that the integration aspect is of prime importance to achieve this range. A revisited classical design of Lockheed could hardly get a 7,500km range at Mach 6 based on hydrogen even after an intensive MDO-process. Innovative designs paying attention to the multi-disciplinary integration have a potential to get beyond close to a 16,000km range at a Mach 8 flight speed.

The different tools to cross-check or predict the efficiencies of the vehicle, e.g. for propulsion or aerodynamics, are gradually put in place and verified to either dedicated basic or more applied experiments for these disciplines. In the meantime, advanced materials, cooling techniques and structural architectures are studied to cope with the high heat loads and temperatures encountered on particular spots on the fuselage and the combustion chamber.

Finally, the HEXAFLY project initiates now a feasibility study evaluating the complexities involved to experimentally fly-test these radically new conceptual designs accompanied with several breakthrough technologies on board of a high-speed vehicle. If this could be followed up by a flight project, this would increase drastically the Technology Readiness Level (TRL) up to 6 (System demonstrated in relevant environment). • *Johan Steelant*

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'Aero-Thermodynamic Loads on Lightweight Advanced Structures II' project investigating high-speed transport. ATLLAS II, coordinated by ESA-ESTEC, is supported by the EU within the 7th Framework Programme Theme 7 Transport, Contract no.: ACP0-GA-2010-263913. Further info on ATLLAS II can be found on http://www..esa.int/techresources/atllas_II.

'High-Speed Experimental Fly Vehicles' project investigating the feasibility of flight experiments for civil high-speed transport. HEXAFLY, coordinated by ESA-ESTEC, is supported by the EU within the 7th Framework Programme Theme 7 Transport, Contract no.: ACP0-GA-2012-321495. Further info on HEXAFLY can be found on http://www.esa.int/techresources/hexafly.

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