Comparative Study on Options for High-Speed Intercontinental Passenger Transports: Air-Breathing- vs. Rocket-Propelled

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This paper investigates the technical options for high-speed intercontinental passenger transports on a preliminary basis. Horizontal take-off hypersonic air-breathing airliners are assessed as well as vertical take-off, rocket powered stages, capable of a safe atmospheric reentry. The study includes a preliminary sizing and performance assessment of all investigated vehicles and compares characteristic technical and passenger environment data.

The aerodynamic shape of the air-breathing hypersonic airliners is defined to fulfill the L/D and range requirements. The propulsion system including air-intake and nozzle is integrated into the preliminary design. The rockets are based on an advanced but technically conservative approach not relying on exotic technologies. The two stage, fully reusable vehicle is designed as an "exceedingly reliable" system to overcome the safety deficits of current state-of-the-art launchers. An engine-out capability is integrated for example. The analysis critically assesses the technical options, technology demands, and tries to evaluate the available options on a sound basis.

Supported by the results of the technical study, some programmatic issues concerning space flight are finally discussed. A preliminary cost analysis of the rocket powered vehicle gives an indication on the economic feasibility and its impact on launch vehicle production. The development of very high speed intercontinental passenger transport might enable, as a byproduct, to considerably reduce the cost of space transportation to orbit.

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
M	Mach-number	-
T	Thrust	N
W	weight	N
g	gravity acceleration	m/s^2
m	mass	kg
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

AOA	Angle of Attack
CAE	Computer Aided Engineering
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
GLOW	Gross Lift-Off Mass
HSCT	High Speed Civil Transport
ICBM	Intercontinental Ballistic Missile
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LEO	Low Earth Orbit
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
NPSP	Net Positive Suction Pressure
RBCC	Rocket Based Combined Cycle
RLV	Reusable Launch Vehicle
SSME	Space Shuttle Main Engine
SSTO	Single Stage to Orbit
TBCC	Turbine Based Combined Cycle
TSTO	Two Stage to Orbit
cog	center of gravity
sep	separation

1 INTRODUCTION

Since the demise of Concorde operation, intercontinental travel is restricted to low-speed, subsonic, elongated multi-hour flight. However, the scientific and political interest in hypersonic passenger airliners is still alive, as has been recently demonstrated by an ongoing European Union (EU) research project. Conventional wisdom assumes to operate these transport craft, depending on the flight Mach-number, by combined air-breathing turbo-jet-RAM-, or SCRAM-engines.

Although these propulsion systems seem to be feasible in principle, their utilization is still quite far away in the future due to technical challenges, development-, and operational cost. The technical demonstration of SCRAM has reached the subscale level at best. An interesting alternative in the field of high-speed intercontinental passenger transport vehicles might be a rocket-propelled, suborbital craft. The functionality of rocket propulsion is a proven technology since decades.

Such a rocket engine powered vehicle would rapidly climb out of atmosphere, accelerate to about 7 km/s, and be able to reach its destination 15000 to 18000 km

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downrange in slightly more than 1 hour. The flight durations are two to three times lower than those of even the most advanced airbreathing systems. On the downside, rocket propulsion is up-to-date inherently less reliable than air-breathing engines and its life time is considerably lower.

This paper starts a systematical investigation on the technical options for high-speed intercontinental passenger transports. Horizontal take-off hypersonic air-breathing airliners are assessed in chapter 2 as well as vertical take-off, partially ballistic rocket powered stages in chapter 3. The baseline assumptions for all vehicles are similar, as far as possible, and the implemented analysis tools are identical.

Supported by the results of the technical study, some economic and programmatic issues concerning space flight are finally discussed in chapter 4.

2 AIR-BREATHING CONCEPTS FOR HIGH-SPEED INTECONTINENTAL FLIGHT

Currently, an ongoing EU study called LAPCAT addresses advanced high-speed air-breathing propulsion concepts [1]. The first scientific and technological objective of the multinational research project is further outlined in [1] as:
"… to evaluate two advanced airbreathing concepts: a Turbine or Rocket Based Combined Cycle (TBCC/RBCC) capable of achieving the ultimate goal to reduce long-distance flights, e.g. from Brussels to Sydney, to less than 2 to 4 hours. Two reference vehicles including their characteristic trajectory points have to be established."

In LAPCAT the definition of both reference vehicles and their trajectories has been performed by DLR-SART. The statement on the Brussels to Sydney route translates into a range requirement of at least 16700 km along the orthodrome and hypersonic flight conditions.

The design approach has been structured as:

- Identification of past projects on similar hypersonic cruise airplanes
- Critical recalculation of the past projects
- Definition of the baseline flight vehicles by adaptation and improvement of the investigated concept

2.1 Supersonic Cruise Airplane at Mach 4.5

In 1990 NASA Langley and Lockheed Engineering & Sciences Company conducted a study to configure and analyze a 250-passenger, Mach 4 high-speed civil transport with a design range of 6500 nautical miles (12045.8 km) [2]. The design mission assumed an all-supersonic cruise segment and no community noise or sonic boom constraints. The study airplane was developed in order to examine the technology requirements for such a vehicle and to provide an unconstrained baseline from which to assess changes in technology levels, sonic boom limits, or community noise constraints in future studies [2].

The general arrangement of the airplane is illustrated in Figure 1. The concept employs a blended wing-body with a modified blunt nose, a highly swept inboard wing panel, and a moderately swept outboard wing panel with curved, raked wingtips. Total length of the vehicle reaches almost 95 m.

Four advanced afterburning turbojet engines are mounted in two nacelles on the wing lower surface adjacent to the fuselage. The propulsion system selected for the NASA-study consists of four conceptual single-rotor, augmented (afterburning) turbojets using thermally stabilized jet fuel.

The Lockheed-NASA estimated dry weight is given at 130 Mg and with 288 Mg kerosene propellant the total lift-off weight including crew, passengers, and their luggage reaches 448 Mg. This mass estimation could not be fully attested by a DLR-SART calculation. In any case the LAPCAT mission range is by almost 40 % larger than NASA's 12000 km, which requires a re-design.

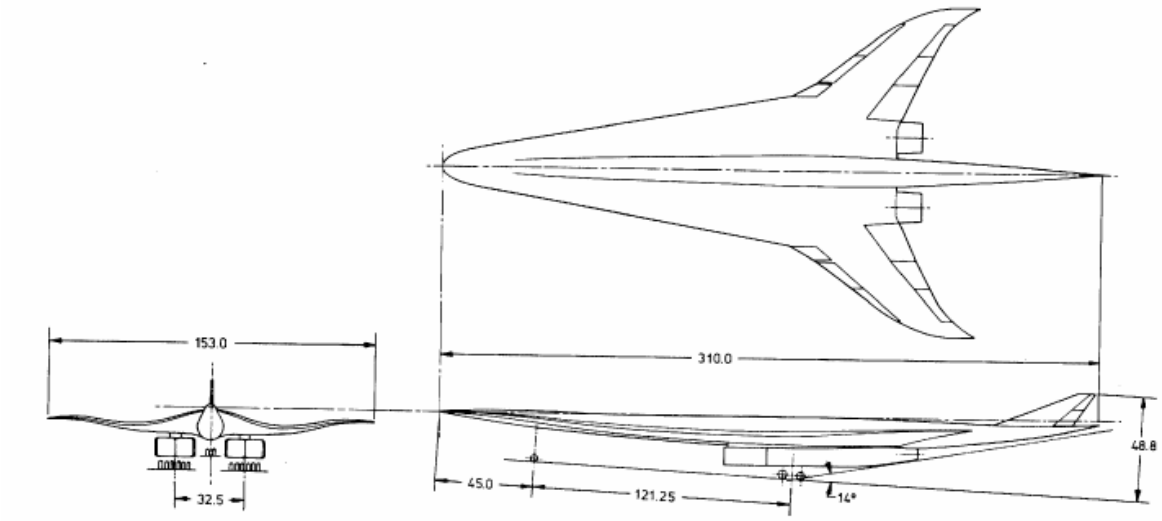

Figure 1: NASA Mach 4 supersonic cruise airplane proposal from 1990 [2] (all dimensions in ft)

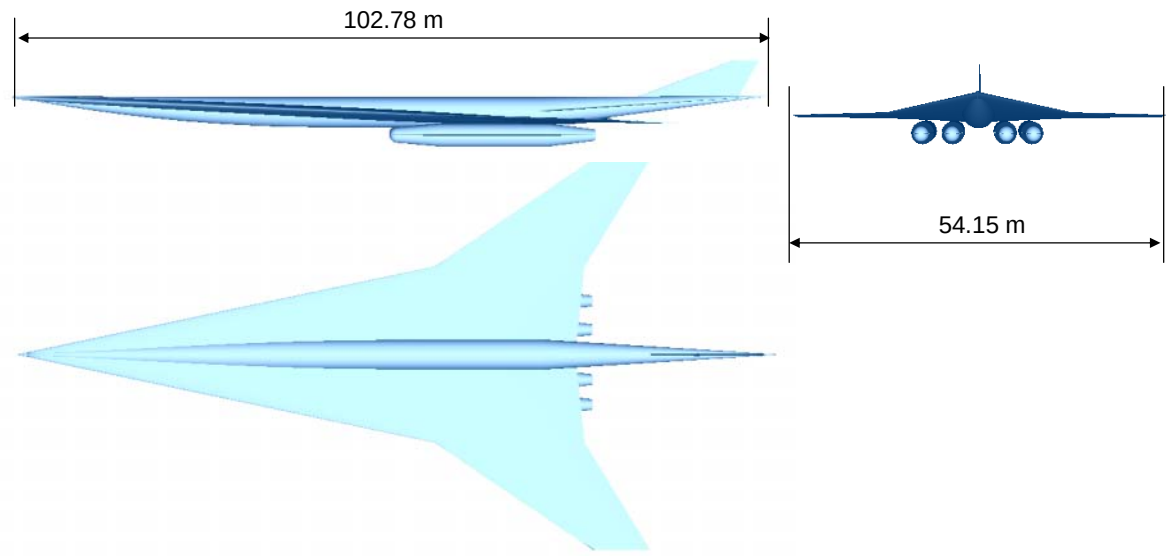

Figure 2: Generic Mach 4.5 supersonic cruise airplane of LAPCAT study (nacelle design not representative)

The new generic supersonic cruise airplane for LAPCAT has to be considerably enlarged compared to the earlier NASA design to meet its ambitious range requirement. To keep the wing loading in an acceptable range the wing size has been increased to 1600 m^2 (+ 36%). The span grows almost proportionally by 16 %, while the total length reaches 102.78 m which is only slightly longer (+ 8.8 %) than the HSCT proposal. The generic geometry of the LAPCAT configuration is shown in Figure 2. The large, slightly inclined wing might help to achieve a good maximum L/D of 7.8 at a small angle of attack and cruise Mach number 4.5 according to preliminary DLR-analysis. Actually, a high L/D is essential to achieve the ambitious range requirement.

The NASA selection of four conceptual single-rotor, augmented (afterburning) turbojets remains a baseline. However, the engine type is slightly changed from pure augmented turbojet to combined Turbo-RAM propulsion to enable an increased cruise Mach number of up to 4.5. Other turbine based propulsion options will be investigated by the LAPCAT partners in the future.

The total take-off mass of the supersonic cruise airplane is iterated to the enormous value of 702.6 Mg, which is well beyond any aircraft built to date. The dry mass is estimated at 178 Mg and the structural index is at a for airplanes low 36.5 %. According to current data the LAPCAT-M4 would be able to transport 342 passengers with their luggage. That value might look oversized but the configuration had not been further iterated to a smaller number of passengers. The high sensitivity of the configuration to mass changes and the ambitious mass goals of some components give some likelihood that the passenger number will automatically shrink with more detailed investigation.

After about a one hour climb to its cruise altitude, the LAPCAT-M4 configuration is simulated to fly along an optimum trajectory [4] for a fixed cruise Mach number of 4.5. Depending on the vehicle mass, the altitude varies between 24400 m and 29100 m. After approximately 14500 s (4 hours) of flight along the orthodrome the supersonic cruise airplane should reach its final destination. The overall flight environment for passengers inside the cabin in terms of acceleration loads is very similar to that in conventional subsonic airplanes. After horizontal take-off the axial load factor does not exceed 0.15 g and the nominal normal load factor is around 1 g. However, according to FAA/EASA standards the airframe and the passengers aboard are required to withstand maximum off-nominal n_z loads at up to 2.5 g.

Obviously, some of the assumptions on the propulsion system performance, the structural mass, and the groundtrack routing with over flying populated areas are quite optimistic. On the other hand, the preliminary design proves that a Mach 4+ passenger cruise airplane with an interesting intercontinental range is not fully out of reach.

The most critical points of a LAPCAT-M4 like vehicle are identified as:

- Very high supersonic cruise L/D close to 8 is required
- High performance propulsion system with extremely high pressure recovery
- Ultra light-weight structural design in high load, high temperature environment
- Environmental impact of noise and on the atmosphere not yet sufficiently solved.

2.2 Hypersonic Cruise Airplane at Mach 8

Historically, the proposals on hypersonic cruise airplanes seem to be much rarer than those on supersonic airliners. This is obviously due to the fact that there exists a considerably more demanding thermal environment. The very high heat flux at sufficient dynamic pressure for the airbreathing engines almost excludes any sustained hypersonic flight.

An innovative concept dubbed *HyperSoar* has been proposed by Lawrence Livermore National Laboratory in the US. The vehicle concept found a large public interest when it was illustrated on the title of Aviation Week & Space Technology magazine in 1998 [5]. Designed as a global reach military strike airplane with a flight Mach number of 10, HyperSoar has a unique feature of skipping on the upper atmosphere (see Figure 3). After accelerating with Rocket Based Combined Cycle (RBCC) engines, the vehicle would temporarily shut down its propulsion system and begin a periodic hypersonic cruise trajectory. While the configuration is outside the dense layers of the atmosphere the propulsion system and leading edges could cool down. When it falls back the Scramjet of the RBCC is reignited for a short period to accelerate again for another ballistic arc.

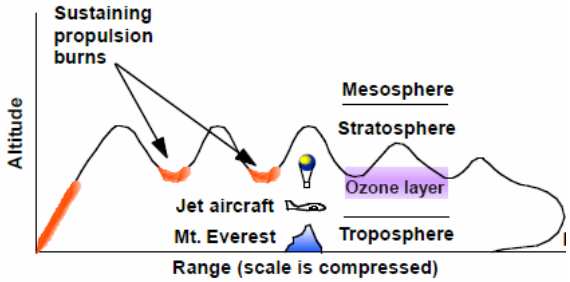

Figure 3: Principle idea of HyperSoar trajectory

In the course of continued research in the US, the notional design of the HyperSoar 1998 vehicle was improved using "Osculating Cone waverider" design. Figure 4 shows the layout of this improved shape. The inlet airflow requirements of the propulsion are more adequately addressed and the aft-body shape and flight control layout are more realistic in this design. DLR-SART has recalculated the HyperSoar 2000 configuration. The recalculation should help develop the tools for a similar but larger LAPCAT-M8 hypersonic airliner. Independent mass assessment of the HyperSoar 2000 configuration with the DLR mass analysis tool *stsm* based on similar dimensions and loads delivers an empty weight of 94500 kg (+ 80% compared to data provided in [5]). With a similar amount of propellant (146200 kg + 10000 kg reserves) and a new take-off mass (256200 kg) an intercontinental range with a payload of about 10000 kg nevertheless does not seem to be completely out of reach.

Figure 4: Artists impression of the HyperSoar 2000 configuration

Almost no data can be found on the propulsion system performance characteristics of HyperSoar. The concept developer at LLNL, Preston Carter, published a paper on periodic hypersonic cruise [6]. This study used an ejector RAMJET/SCRAMJET rocket engine. Therefore, it seems quite reasonable that a very similar RBCC is the basic propulsion system of HyperSoar. The specific impulse model as presented in [6] seems to be very simplified, at least on the ejector rocket side. Very limited historical data of experiments or flight tests on air-augmented rockets have been published. So far as has been publicly admitted, there has been only one serious attempt to make a production air-augmented launch vehicle or ICBM, the Soviet Gnom design which represented the most advanced work ever undertaken on an air-augmented missile. The project was cancelled at the end of 1965 but is said to have flight demonstrated an I_{sp} of 550 s with a solid motor ejector rocket [7].

The preliminary performance assumptions of the generic LAPCAT hypersonic cruise airliner in the ejector mode operation are more conservative than those of Hyper-Soar. The still very simple model reaches a maximum I_{sp} of 626 s at M= 2.5. The following transition to pure air-breathing operation sharply increases I_{sp} to 3700 s while reducing the thrust level by more than 50 %. This hypothesis seems to be quite reasonable but has to be checked by establishing better thermodynamic com-putational models within the LAPCAT study.

The new generic hypersonic cruise airplane for LAPCAT has been based on the HyperSoar 2000 shape despite some concerns on its flyability. However, for defining the size and the propulsion system thrust requirements this approach is still acceptable. LAPCAT-M8 is considerably enlarged compared to HyperSoar to accommodate the passengers and the cabin and to meet the ambitious LAPCAT range requirement.

To keep the wing loading within an acceptable range the lifting body's projected area has been increased to 3000 m^2 (+ 150 %). The span grows to 34.2 m, while the total length reaches 106.1 m (+ 74 %) when compared to HyperSoar 2000. The generic geometry of the LAPCAT configuration is shown in Figure 6. The waverider shape achieves a maximum hypersonic L/D of 4.2 at a small angle of attack according to preliminary DLR-analysis [3]. The simulations show that the periodic cruise trajectory is much less sensitive to L/D than steady state cruise.

The choice of high energy but low density hydrogen complicates the accommodation of the tanks inside the relatively flat waverider shape. Tank sizing is performed with *pmp*, a DLR tool under development for rapid tank, feedline, and pressurization system analysis, design and corresponding mass estimation. Tank mixture ratio depends on the duration of the rocket mode and the length of the pure air-breathing ram-scram mode. Including residuals, the tanks have to be capable of loading at least 507500 kg LOX and LH2 propellant. Figure 5 shows the large hydrogen tanks to be filled with 335750 kg LH2. The comparatively small tanks on each outboard are loaded with oxygen.

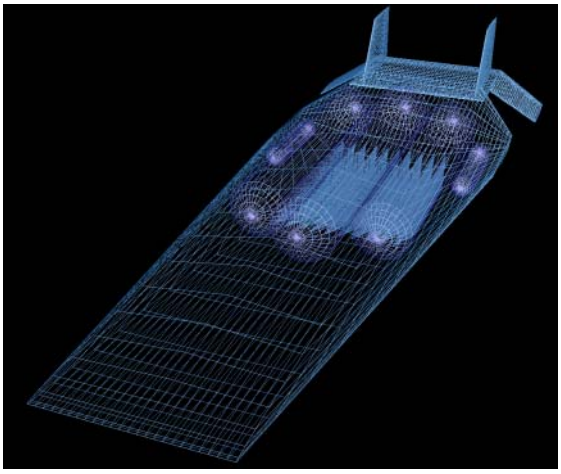

Figure 5: Accomodation of tanks inside the waverider shape of LAPCAT-M8

Climb and cruise fuel fractions are used from trajectory simulations of the actual LAPCAT-M8 configuration. The total take-off mass of the hypersonic cruise airplane is iterated to the enormous value of 761.4 Mg, which is also well beyond any aircraft built to date. The dry mass is estimated at 242.3 Mg and the structural index is at 47.8 % considerably higher than for LAPCAT-M4. According to current data the hypersonic vehicle with cruise Mach beyond 8 would be able to transport 100 passengers with their luggage. The relatively high dry mass is due to the large fuselage surface area and the outsize hydrogen tanks with up to 45 m in length. The severe thermal conditions in the skipping phase of the trajectory would not have allowed a cylindrical integral tank structure.

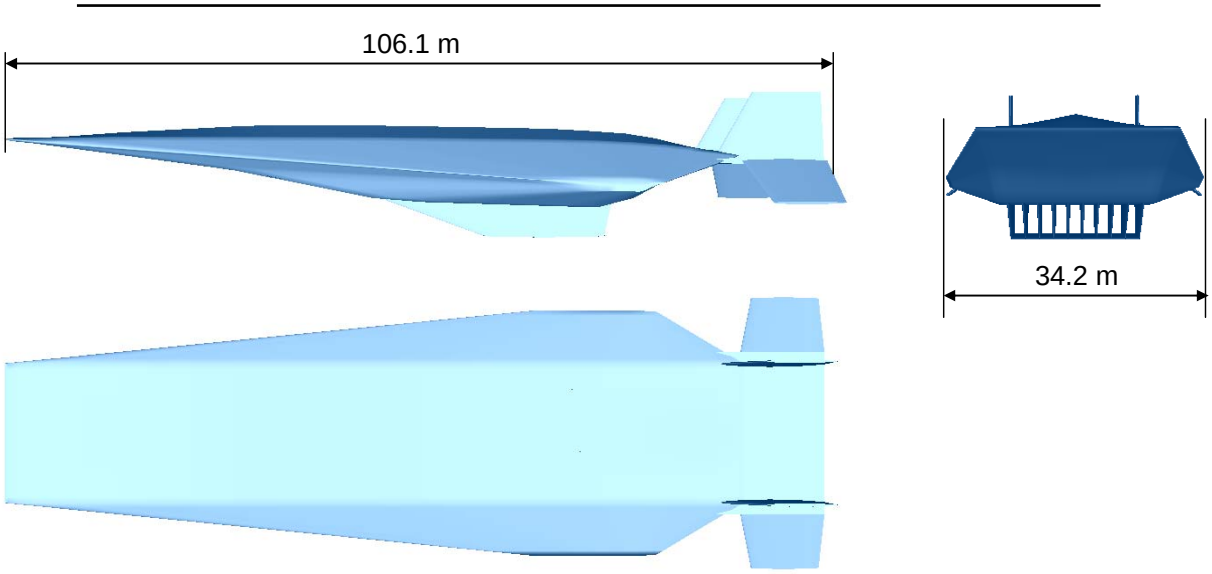

Figure 6: Generic Mach 8+ hypersonic cruise airplane of LAPCAT study

The mission is flown in the ejector mode up to a Mach number of 2.5 when switching to pure air-breathing RAM-SCRAM-mode is performed. Sophisticated control algorithms have been implemented in the DLR-tool *RFD* to enable the full simulation of a stable skipping trajectory. Trajectory constraints are a maximum load factor of n_z= 1.6, and a maximum dynamic pressure q of 50 kPa. After a good acceleration, mostly carried out by its powerful rocket engines, the LAPCAT-M8 configuration reaches the periodic cruise condition in slightly more than 10 minutes. During that time the initial take-off mass of the vehicle is already reduced by more than 250 Mg to slightly above 500 Mg. The axial load factor does not exceed 0.85 g. The periodic cruise Mach number alternates between 9 and 7 while the altitude varies between 32000 m and 50000 m (see Figure 7).

The leading edge heat flux is critical for the overall design. During the hot acceleration phase the adiabatic equilibrium temperature is estimated to exceed 1400 K and in the relatively cool ballistic phase this temperature should reach values above 800 K. The actual temperature on the leading edges can thus be expected beyond 1100 K.

After approximately 6800 s (1.9 hours) of flight along the orthodrome the hypersonic cruise airplane should reach its final destination. The overall flight environment for passengers inside the cabin in terms of acceleration loads is very different to that in conventional subsonic airplanes. After horizontal take-off the axial load factor reaches a maximum of 0.85 g while the nominal normal load factor remains around 1 g. However, during the periodic cruise the axial acceleration varies between -0.3 g (drag deceleration) and +0.8 g (SCRAMJET acceleration). The normal load factor is found to be close to weightlessness in the ballistic arc and +1.6 g in the lower skipping points.

According to FAA/EASA standards the airframe and the passengers aboard are required to withstand maximum off-nominal n_z loads up to 2.5 g. The LAPCAT-M8 comfortably stays within these limits. However, the load

frequency (with a period of approximately 200 s) is much different to that in conventional passenger aircraft.

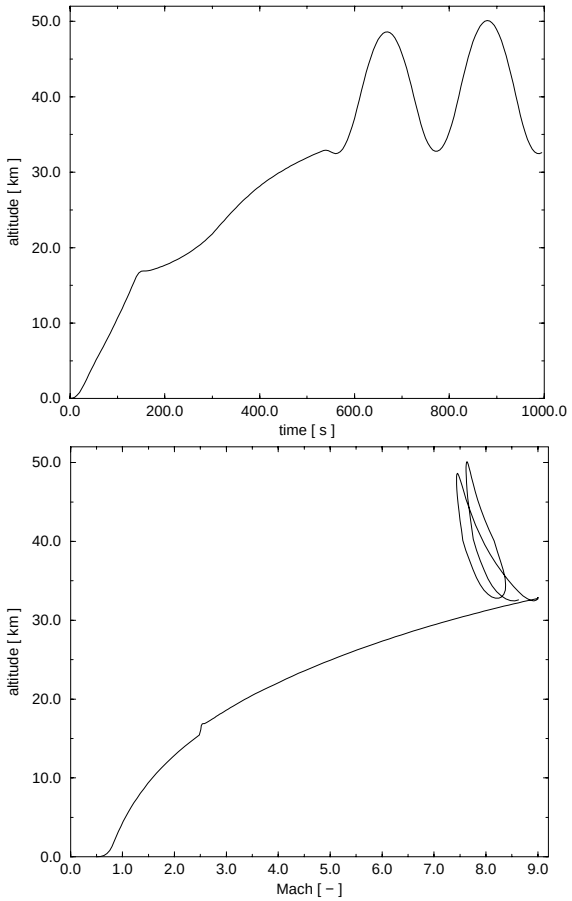

Figure 7: Trajectory conditions of LAPCAT-M8 in the first 1000 s after take-off

Obviously, some of the assumptions on the ejector rocket propulsion system performance, the structural mass, and the groundtrack routing with over flying populated areas are quite optimistic. On the other hand, the preliminary design proves that a Mach 8+ passenger cruise airplane with an interesting intercontinental range is not fully out of reach.

The most critical points of a LAPCAT-M8 like vehicle are identified as:

- RBCC requires ejector nozzle operation at low Mach number flight. Only poor performance data is available for the propulsion system. Performance of RBCC is however highly critical to the overall feasibility
- Large scale intermittent SCRAM propulsion is yet to be demonstrated
- Ultra light-weight structural design in high load, very high temperature environment
- Waverider like configuration raises strong concerns on trimmability
- Skipping trajectory is not overly attractive considering passenger comfort
- Environmental impact of noise and on the atmosphere not yet sufficiently solved.

The high fuel consumption of 180 Mg in the first 200 s after lift-off is due to the relatively poor I_{sp} of the ejector rocket. As an alternative, a turbine based cycle (TBCC) has also been briefly investigated. Although the fuel consumption of the TBCC is much lower, the acceleration is also significantly reduced and the propulsion system becomes considerably heavier. Thus, according to a first preliminary analysis only a slight decrease in the 760 Mg take-off mass is to be expected when changing the propulsion system from RBCC to TBCC. Integration of turbojet engines into the LAPCAT-M8 configuration as shown in Figure 6 is quite difficult. Therefore, the RBCC propulsion system is currently kept as a baseline.

3 ROCKET-PROPELLED INTER-CONTINENTAL PASSENGER STAGE

The rocket engine powered vehicle is based on an advanced but technically conservative approach which does not rely on any exotic technologies. From an operational point of view, a single stage configuration would have been preferable. However, the minimum Δv-requirement of 7000 m/s without losses would have required SSTO technology and would have nevertheless resulted in a very large and outsize stage. Thus, a two stage, fully reusable vehicle is designed as an “exceedingly reliable” system to overcome the safety deficits of current state-of-the-art launchers. The cryogenic propellant combination LOX-LH2 is selected for its superior performance characteristics.

Different configurations and take-off modes have been analyzed [8]. Horizontal take-off options, which are far more conventional for passenger flight, have been dismissed because of unsolved problems related to cryogenic propellant sloshing and rocket engine feed. Moreover, in this case an unproven sled launch would be required because no take-off gear is imaginable for the high mass and velocity required. A parallel stage arrangement is preferred over a tandem configuration mostly due to the latter’s expected outsize length of more than 100 m. The large wings of the two reusable stages in tandem arrangement would generate high bending loads on the structure.

In contrast to the air-breathing cruise vehicles of chapter 2, no similar rocket propelled multiple stage launcher of historical studies has been used as a reference. However, reusable TSTO concepts like the LFBB derived configuration of DLR [9] or the French EVEREST launcher [10] which have been designed for payload delivery to orbit come quite close with their overall architecture. Another starting point for the design of the second stage is the Space Shuttle orbiter. Although the reusable upper stage with the passenger payload called "SpaceLiner" does not reach stable orbital velocity during nominal missions of the reference design, its conditions are so similar to those of an orbiter that the vehicle is also dubbed as 'orbiter' in the following paragraphs.

The booster and orbiter engines are assumed to be identical for the baseline configuration. All engines should work from lift-off until MECO. A propellant crossfeed from the booster to the orbiter is foreseen up to separation to reduce the overall size of the orbiter stage. Fuel rich staged combustion cycle engines with a moderate chamber pressure, 1700 kN thrust and 448 s I_{sp} in vacuum are assumed for the propulsion system. These

engine performance data are not overly ambitious and have already been exceeded by existing engines like SSME or RD-0120. However, the ambitious goal of a passenger rocket is to considerably enhance reliability and reusability of the engines beyond the current state of the art.

A basic requirement for the overall design of the 'SpaceLiner' concept is an acceptable safety record. The specific number of fatalities in its operation should not exceed those of early jet-airliner travel. It has to be realized that such a requirement is a notable technical challenge in itself, far beyond the capability of today's manned spaceflight. In a first approach, the rocket engines are intentionally not designed to their technical limits to improve their reliability. Intensive testing and qualification of the propulsion system is further essential. Nevertheless, an engine-out capability during all acceleration flight phases is to be integrated. Despite all effort, tight margins are intrinsic of all launch systems and significantly reduce the achievable safety and reliability. Thus, a passenger rescue system will be indispensable. This could be envisioned as the cabin in form of a large capsule to be separated from the orbiter in case of an emergency and then safely returning to Earth.

The size of the vehicle is iteratively found in combination of mass estimation and trajectory simulation. Depending on different trajectory options after orbiter MECO (discussed below) an optimum configuration of minimum size has been defined. The overall length of the passenger spaceplane SpaceLiner is 63 m (see Figure 8 for the launch configuration including booster). The booster is a large unmanned tank structure providing thrust and propellant crossfeed to the orbiter up to staging. The orbiter accommodates 180 Mg propellant in the aft section which is designed as an aeroshell-like concept. Aerodynamic considerations and severe thermal conditions in the atmospheric skipping phase exclude any integral tank structure.

The total take-off mass of the SpaceLiner configuration in the reference lay-out is 905 Mg. This value is in the same class as for other proposed reusable TSTO. The total lift-off mass of the Space Shuttle is much higher in contrast; but the Space Shuttle is designed for increased payload capability to higher circular orbits and has a lower average specific impulse due to its solid motors. The combined dry mass of both SpaceLiner stages is estimated at 183.8 Mg and the structural index is at 26.2 %. The latter is relatively conservative for a large cryogenic RLV. However, it has to be considered that the vehicle has to include a passenger cabin and safety features. The spaceplane is designed to transport 50 passengers with their luggage.

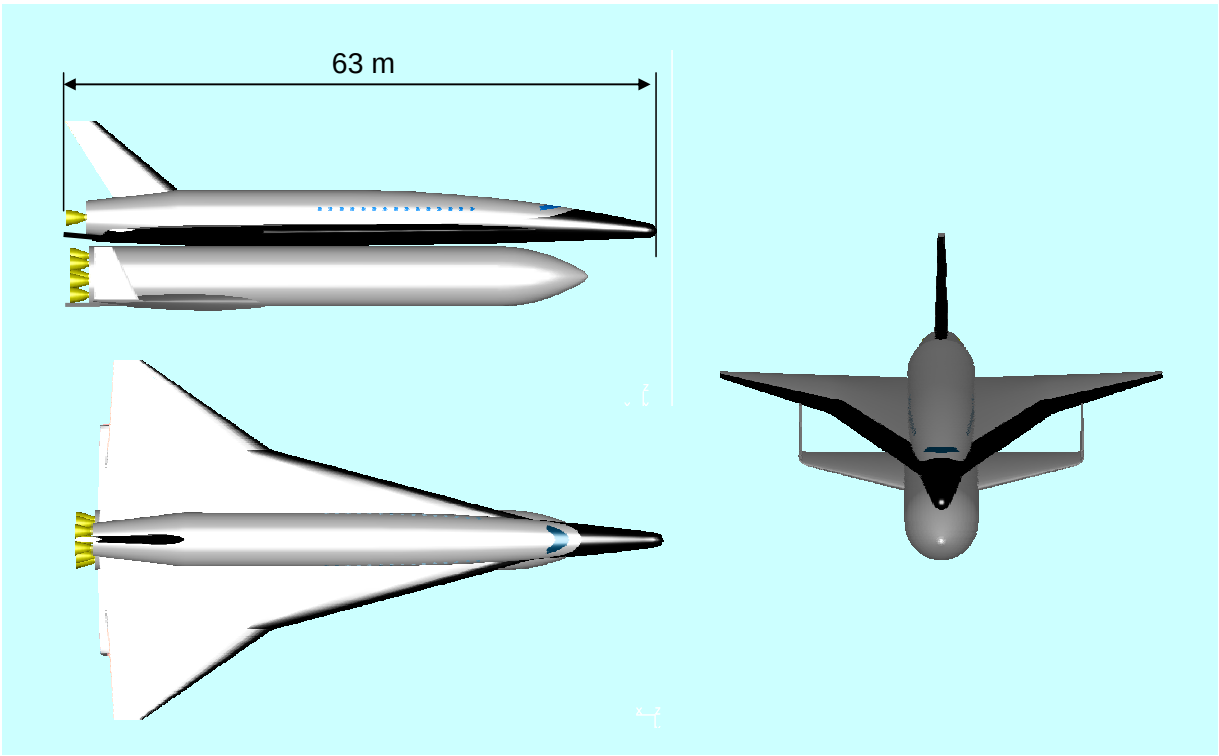

Figure 8: Generic rocket powered intercontinental passenger spaceplane SpaceLiner with booster

Different SpaceLiner trajectories with intercontinental destinations have been analyzed. One of the most demanding missions is the west-bound flight from south-east Australia to a central European destination which is selected as the reference design case in this study. After performing a vertical take-off, the combined launcher accelerates for 160 s up to 2.5 km/s (Mach 9) when the booster separates. The booster main engines are throttled when the axial acceleration reaches 2.5 g. After its MECO the booster performs a ballistic reentry and should be transferred back to its launch site. A classical technical solution is the powered fly-back by turbojet engines because the distance is by far too large for a simple glide-back. An innovative alternative is the capturing of the reusable stage in the air by a large

subsonic airplane and subsequent tow-back. This patented method dubbed 'in-air-capturing' has been investigated by DLR in simulations and has proven its principle feasibility [11, 12]. The massive advantage of this approach is the fact that a booster stage caught in the air does not need any fly-back propellant and turbo-engine propulsion system. The mass savings on the RLV stage by in-air-capturing allow for a significantly smaller vehicle or a payload increase [11]. The innovative capturing has been selected as the baseline technology for the booster retrieval, enabling a total lift-off mass reduction of at least 150 Mg. Conventional turbojet fly-back is a backup option, if 'in-air-capturing' would be deemed as unfeasible or as too risky.

Following separation, the orbiter with the passengers inside accelerates for another 260 s to MECO conditions close to 7 km/s at a relatively low altitude of 110 km. Different flight options exist in principle after MECO. Those which have been assessed in flight simulation with the DLR-tool *RFD* are:

- long ballistic phases with different flight path angle at the atmospheric entry interface, and
- atmospheric skipping with slight differences in initial conditions.

The parametric variations performed with MECO conditions at 7100 m/s and 122 km showed that all options with a relatively long ballistic phase of a few thousand seconds have a considerably lower range than the atmospheric skipping [8]. The extremely high reentry loads with the orbiter in a steep flight path angle exclude any practical application of the long-time ballistic option. The load factors as well as the heat flux will exceed all acceptable limits for manned flight in a reusable vehicle. This result is obviously completely different for the military application of warheads.

The atmospheric skipping alternative looks much more attractive, though still highly demanding. Not only can the achievable flight range be increased by about 70 % compared with ballistic flight at the same initial conditions. Moreover, the mechanical loads during the skip phases can be controlled within limits very similar to those of the HyperSoar vehicle described in section 2.2. Although the stagnation point heat flux is much lower than in the ballistic option, it might exceed 4 MW/m^2 for a short time [8] because it has to fly with a Mach number of around 20 at altitudes as low as 50 km (see Figure 9). According to a preliminary estimation the adiabatic equilibrium temperature might exceed 3000 K in the nose and leading edge regions. Those data indicate highly challenging conditions for the materials and thermal protection.

After approximately 5200 s (1.4 hours) flying along the orthodrome, the SpaceLiner should reach its final destination. The overall flight environment for passengers inside the cabin with respect to acceleration loads is, as expected, very different to conventional subsonic airplanes. After a vertical take-off the axial load factor reaches a maximum of 2.5 g achieved by engine throttling. During that period the nominal normal load factor remains considerably below 1 g. After about 200 s of 0 g weightlessness following MECO, the skipping trajectory starts. The periodic drag deceleration never exceeds -0.2 g. The normal load factor has a nominal design maximum of +1.5 g and a minimum of 0.1 g in the first skip and succeeding ballistic arc. Afterwards both extremes are closing in on the normal flight condition of 1 g.

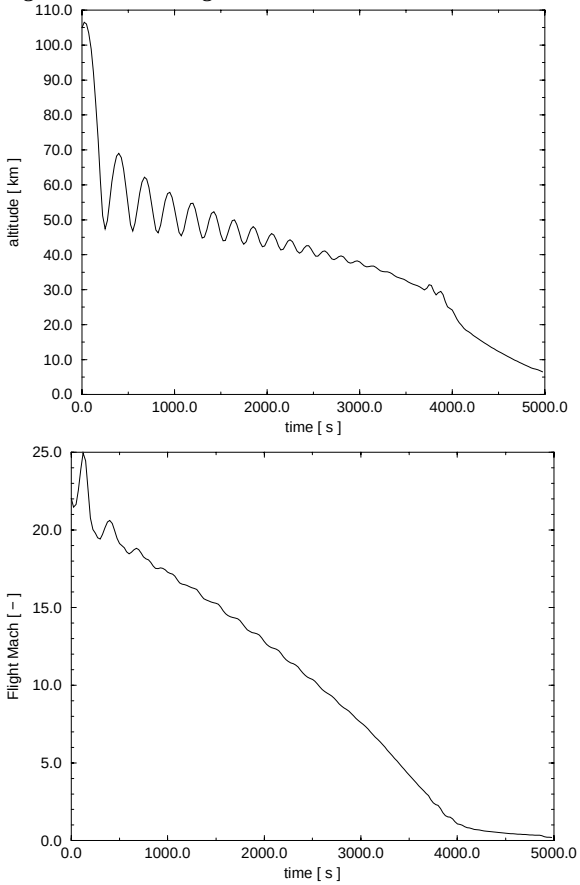

Figure 9: Altitude and Mach number of SpaceLiner after MECO with skipping trajectory

According to FAA/EASA standards the airframe and the passengers aboard are required to withstand maximum off-nominal n_z loads up to 2.5 g. The SpaceLiner comfortably stays within these limits. However, the load frequency (starting with a period of approximately 300 s) is much different to that in conventional passenger aircraft.

The negative environmental impact of the LOX/LH2 powered rocket SpaceLiner seems to be much less critical than that of the two airbreathing concepts of chapter 2. The engines do not pollute the atmosphere with nitrogen oxides because they do not use the air. Most of the flight trajectory is at a much higher altitude than for the airbreathing vehicles considerably reducing the noise impact on ground. Nevertheless, the launch has to most likely be performed off-shore because usually no remote, unpopulated areas are found close to the business centers of the world. Consequently decoupling of the launch and landing site will create some logistical challenges.

The most critical points of a rocket based passenger vehicle like the SpaceLiner concept are identified as:

- Reliability and safety of the liquid rocket engine based propulsion system
- Very light-weight structural design in high load, extremely high temperature environment for the orbiter

- Skipping trajectory is not overly attractive considering passenger comfort
- Fast turn-around times currently unknown in the launcher business.

The highly challenging technical issue of the extremely high heat flux might be circumnavigated if the SpaceLiner would achieve a low but stable, almost circular orbit. After performing a section of a full orbit's ballistic arc, the vehicle can be conventionally decelerated for controlled reentry with on board engines. The following atmospheric entry could be kept within mechanical and thermal loads of existing orbiter vehicles like Space Shuttle or Buran. This approach might also be more comfortable for the passengers inside. On the downside this solution would require several hundred m/s additional Δv resulting in a much heavier launcher and heavier and larger orbital stage. Therefore, the low orbital option is only a backup in case the reference skipping variant should turn out to be technically unfeasible or too risky.

4 COMPARISON AND PROGRAMMATIC OPTIONS

The study of the high-speed, long haul passenger transports revealed clear differences between the three main configurations. These will be addressed and evaluated in the first section of this chapter. In the second section preliminary operation and cost analyses are performed for the rocket powered reusable stage. A parametric evaluation of achievable ticket prices checks, if a business case might exist for the huge investment. Resulting launch vehicle production requirements are assessed with respect to those of current space launchers. Some programmatic options on space flight are deduced.

4.1 Comparison of Characteristic Data for the High-Speed Concepts

The major interest in all high-speed intercontinental passenger transports is a significant reduction in flight duration. Travel times of up to more than 20 hours are not unusual for long haul distances like Europe - Australia or East Asia - North East America. Table 1 lists the flight times from take-off to landing of the Mach 4.5, Mach 8+, and the rocket powered vehicles. Additional check-in and commuter times are to be added as with today's subsonic airliners. The latter might increase because fewer launch and landing facilities will most likely be available for the high-speed craft than with the current subsonic infrastructure. Nevertheless, a reduction in total travel time between 50 % and 80 % seems to be achievable which would be sufficiently attractive for the increased ticket price. Note the decreasing passenger numbers with reduced flight time.

		LAPCAT-M4	LAPCAT-M8	SpaceLiner
Flight time	h	4.0	1.89	1.44
passengers	-	342	100	50
maximum n_x	-	0.15	1.05	2.5
minimum n_x	-	-0.05	-0.3	-0.18
maximum n_z	-	1.05	1.6	1.5
minimum n_z	-	0.94	0.2	0

Table 1: Passenger flight environment of the different transportation options

All loads on the passengers are well within the aeronautical standard requirements. A short time axial acceleration of 2.5 g should not generate problems for passengers sitting in their seats. However, the skipping trajectories of the hypersonic airliner and of the SpaceLiner, creating some unusual periodic normal acceleration, are to be checked for acceptable passenger comfort.

The mass characteristics are found in Table 2. It can be noted that the take-off mass is increasing with a reduction in average specific impulse. This general trend can be observed, although the technical solutions (single stage for the airbreathers, two stage for the SpaceLiner) and the actual trajectories and hence losses are quite diverse. Mass and dimensions of the rocket powered vehicle are well within the range of existing launchers, while both LAPCAT airliners significantly exceed mass and dimension of all existing airplanes. The large surface area of the hypersonic waverider is responsible for the quite high dry mass and relatively low structural efficiency of the hypersonic LAPCAT-M8. It has to be noted that a more conservative approach has been applied to the SpaceLiner mass estimation than for the LAPCAT vehicles to take care for enhanced reliability to be included in a rocket powered passenger stage.

The amount of fuel of the rocket powered vehicle is the highest, but only 15 % of the value is hydrogen. For the airbreathing SCRAMJET LAPCAT-M8 it's about two thirds. The amount of hydrogen will be an important aspect in establishing a high-speed transport infra-structure. Today's hydrogen production is far below the requirement of even a low daily flight number (see section 4.2 for a basic scenario). The analyses of this study show that the total hydrogen demand of the SCRAMJET airliner is about three times that of the rocket vehicle.

		LAPCAT-M4	LAPCAT-M8	SpaceLiner
take-off mass	Mg	702.6	761.4	905
dry mass	Mg	178	242.3	183.8
fuel mass	Mg	489.3	507.5	702
structural index	-	0.36	0.477	0.266

Table 2: Mass data of the different transportation options

4.2 Assessment of the SpaceLiner Concept and Programmatic Options for Space Flight

The very high-speed travel option of the SpaceLiner is most attractive on ultra-long haul distances between the main population and business centers of the world. These can be identified at least in Australia, East Asia, Europe, and the Atlantic and Pacific coast of North America. Obviously, more destinations might be of interest but the current study is based on seven flight routes and a daily two way service on each of them.

Thus, a total of 14 launches would be performed each day and 5110 every year. This very number demonstrates that today's launch rate might increase by two orders of magnitude. Taking into account the passenger capacity of 50 for each SpaceLiner voyage, a total of 255000 people might be able to reach space per

year. If an ambitious two day turn around time should be achievable and assuming ten vehicles permanently in heavy maintenance or overhaul, a minimum fleet size of 38 vehicles would be required.

The lifetime of the reusable stages and the engines is an important parameter for the assessment of the operation costs. The Space Shuttle orbiter and more recent studies on RLV are based on a design lifetime of slightly above 100 missions. Engine life should reach between 20 and 50 reuses, although not demonstrated up to now. These lifetime data have been parametrically changed to obtain the average annual production numbers. In a scenario with a moderate reusability requirement of 150 flights for the vehicles and 25 for the engines, an average *yearly* production rate of 34 orbiters and boosters and about 2000 engines will be needed. Obviously, this would be a 'mass production' never seen before in spaceflight but still quite modest compared to large airliners. A sharp increase in the production rate allows, following a standard learning curve approach, a dramatic reduction in unit cost. The complexity of a reusable rocket powered stage and of the rocket engines is not principally higher than that of large airplanes like Airbus A-380 or Boeing B-747 and their respective high bypass turbofans. Thus, also production cost per item should reach a similar cost level.

The total development cost and investment into the infrastructure will be huge. Development and qualification cost of the passenger SpaceLiner might well reach 30 B€. An additional 30 B€ is roughly estimated for the necessary infrastructure and the initial fleet. Despite this significant investment a business case might exist. Table 3 gives the estimated operation costs of SpaceLiner with 14 flights a day and based on the reusability scenario as mentioned above.

average vehicle replacement cost / M€	8857
average engine replacement cost / M€	3066
total production cost / M€	11923
total maintenance cost / M€	4000
total direct operation cost / M€	10220
total operation cost per year / M€	**26143**

Table 3: Operation cost of SpaceLiner per year

One sees that engine and vehicle replacement accounts for a large part of the operation costs due to the limited life time of the components. Maintenance and direct operation costs (including also the necessary commuter transfer of the passengers to the launch site) are to be verified in more detailed analyses in the future. However, these cost data are sufficiently reliable to check under which circumstances and ticket prices a business case might come up. It seems unlikely that the up front investment in development and infrastructure of the private venture for intercontinental high speed passenger travel will be publicly funded. Therefore, it seems necessary to foresee an amortization on the investment which is preliminarily assumed here with 6 B€ per year. Assuming now an average load factor of 90 % and a ticket price for one way travel of 150000 €, the SpaceLiner will be able to generate more than 34 billion € per year (Table 4).

total cost per year / M€	**26143**
yearly amortization of investment / M€	**6000**
total revenues per year / M€	**34492**
profit per year / M€	**2349**

Table 4: Revenue balance of SpaceLiner per year

Thus, the passenger spaceflight business might be able to have a yearly profit of 2.3 billion €. Surely it is to be acknowledged that these are preliminary estimations with a lot of uncertainties. One of the main reservation is if there will be sufficiently enough people willing to pay the fee of 150000 € per flight. This question might be answered with increased confidence if a commercial space flight venture like Burt Rutan's SpaceShip in cooperation with Virgin Galactic or other endeavors will become reality. Such a precursor application allows testing the market and gaining operational experience. The big difference between the SpaceShip approach and the SpaceLiner concept described in this paper is that the latter not only reaches the edges of space but also offers an attractive extremely fast transportation option.

Even in the case that only a very small portion of the upper business travel segment could be tapped by a rocket-propelled intercontinental passenger transport, the resulting launch rates per year would be far in excess of any other credible scenario. This form of space tourism, not only attracting the leisure market, would, as a byproduct, enable to considerably reduce the cost of space transportation to orbit.

The specific space transportation cost to orbit improvement in a SpaceLiner environment can be quantified assuming the usage of then existing infrastructure and a high commonality in flight hardware. However, a dedicated upper stage or at least the integration of a large cargo bay in the orbiter will be required. Considering payload preparation and check-out which is assumed more costly then the transport of people on their sub-orbital trajectory, specific costs between 500 and 1000 €/kg to LEO seem to be realistically achievable. At such orbital transportation price levels a new on orbit market might be generated, further increasing launch rates and hence reducing overall cost.

5 CONCLUSION

Three divergent design options of very high speed intercontinental passenger transports are systematically investigated. Assuming advanced but not exotic technologies, a supersonic turbojet-RAM based airliner, a hypersonic RBCC waverider, and a vertically launched rocket powered two stage space vehicle are able to transport a significant number of passengers over distances of up to 17000 km. Travel times are in the range 1.5 to 4 hours.

The study is not able to give a clear preference on any design option because all concepts are facing strong technical challenges. The two airbreathing vehicles both are very sensitive to their achievable range and to environmental issues. Therefore, both might be severely

restricted in the destinations they are able to actually serve. The RBCC / SCRAM propulsion of the hypersonic aircraft has a low technology readiness level and the technical feasibility of this propulsion system is yet to be demonstrated.

The rocket engines of the vertically launched concept SpaceLiner are well known in their performance characteristics but are also notorious in their low reliability and life time. A significant improvement in that field as well as additional safety measures on the vehicle are indispensable for passenger flights of such concepts. The negative environmental impact of the LOX-LH2 propelled SpaceLiner seems to be much less critical than for both airbreathing concepts. However, its launch sites have most likely to be located off-shore due to noise and safety concerns.

An atmospheric skipping trajectory is found technically attractive for the hypersonic and for the rocket plane. It remains to be seen if the related alternating normal loads are acceptable for passenger comfort. In case of the SpaceLiner a very low orbit exists as a backup to the skipping, also avoiding extreme thermal heat flow. However, this solution would considerably increase the size of the launcher.

A preliminary cost assessment of the SpaceLiner concept has been performed which shows that an attractive business case might exist for high-speed intercontinental passenger flight through space. A significant up-front investment will be necessary. In the cautious case that only a very small portion of today's airlines' upper business travel segment could be tapped by a rocket-propelled intercontinental passenger transport, the resulting launch rates per year would be far in excess of any other credible access to space scenario. This form of space tourism, not only attracting the leisure market, would, as a byproduct, enable to considerably reduce the cost of space transportation to orbit.

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