Environmental Protection

Franco Persiani, Università di Bologna

Hypersonic from 100.000 to 400.000 ft
First Symposium on Hypersonic Flight

Rome, June 30th - July 1st 2014
Transportation system evolution
Transportation system evolution: some arising questions

a) How a Hypersonic Aircraft may impact on the Environment? & How the Environment may impact on a Hypersonic Aircraft?

b) How a Hypersonic Aircraft Fleet may impact on the Environment? & How the Environment may impact on a Hypersonic Aircraft Fleet and its operations?

c) Commonalities and differences between Civil Hypersonic Vs Mil. Hypersonic
Hypersonic & Environment

- Global Atmosphere
- Climate
- Society
- Biological Resources
- Fuel Production
Chain of influences on climate

1. Economy, technology & population
2. Emissions (E)
   - CO₂, CH₄, N₂O, HFC, PFC, NOₓ, SO₂, ...
3. Atmospheric Concentrations (C)
4. Radiative forcing (RF)
5. Climate Change
   - Temperature (ΔT), precipitation (Δp), winds, soil moisture, extreme events, sea level (ΔSL)
6. Impacts
   - Agriculture and forestry, ecosystems, energy production and consumption, social effects
7. Damages
   - Welfare loss (e.g. monetary units)

Increasing relevance

Increasing uncertainty

Report of the Environmental Change Institute - University of Oxford - C.N. Jardine 2005
Atmospheric Chemistry of Aviation Emissions

Aviation is different from other energy-using activities as the majority of emissions occur at altitude, and their influence on the atmosphere can be highly localised and short-lived.

Emissions from aircraft are responsible for other atmospheric chemical processes that also have atmospheric warming consequences.

Aviation emissions are therefore more significant contributors to climate change, than an equivalent amount of carbon dioxide emitted at ground level.
Atmospheric Chemistry of Aviation Emissions

- Combustion of fuel in airplane engines results in emissions of carbon dioxide (CO2) and nitrogen oxides, (termed NOx), as well as water vapour and particulates.

- It is the emission of NOx, water vapour and particulates at altitude that account for the extra impacts of aviation emissions.

- Emission of water vapour at high altitudes will produce contrails.

- Their warming effect is believed to be equivalent to that of carbon dioxide alone.

- The contrails themselves are implicated in the formation of high altitude cirrus clouds (strong warming effect on the atmosphere).
Effect of historic aviation emissions on the heat trapping ability of the atmosphere

Report of the Environmental Change Institute - University of Oxford - C.N.Jardine 2005
Air Transport Sustainability

With the expected three-fold increase in global air travel over the next 30 years, the reliability and environmental impact of air transport systems are becoming critical issues for the future of the flight.
New transportation system

• The introduction of a new transportation system can influence the transportation demand itself.
• Innovations in competing technologies may threat the development of a new transp. system
• Any new transportation system integrates environmental issues
Hypersonic design: the challenge

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

\[ \eta = \frac{T \cdot V_\infty}{m'_H} = \frac{V_\infty}{sfc \cdot H} \]

**R Cruise Range [m] Breguet eq.**

- \( g \) gravity constant [m/s²]
- \( sfc \) specific fuel consumption [kg/s/N]
- \( V \) flight velocity [m/s]
- \( W \) total take-off mass [kg]
- \( W_F \) fuel mass [kg]

**H the fuel energy content [J/kg]:**
- 120 (LHV) and 142 (HHV) MJ/kg for H₂,
- 43.5 (LHV) and 47 MJ/kg (HHV) for kerosene,
- 50.0 (LHV) and 55.5 MJ/kg (HHV) for Methane

Increases with a factor of 2.7 by switching from kerosene to hydrogen.
Hypersonic design: the challenge

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

<table>
<thead>
<tr>
<th>$M_{\infty}$</th>
<th>0.9</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L/D_{\text{max, euler}}$</td>
<td>17.3</td>
<td>10</td>
<td>7</td>
<td>6</td>
<td>5.5</td>
<td>5.2</td>
</tr>
<tr>
<td>$L/D_{\text{max, viscous}}$</td>
<td>19.2</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>7.5</td>
<td>7.2</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.25</td>
<td>0.4</td>
<td>0.57</td>
<td>0.67</td>
<td>0.73</td>
<td>0.77</td>
</tr>
</tbody>
</table>

$L/D_{\text{max}}$ and overall installed max engine efficiency have reverse dependencies on flight Mach number and their product $\eta$ L/D (max cruise efficiency) may be kept constant, (a value of about 3 to 4), by careful designs.

Achieving this goal implies 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 energy content $H_F$.

see J. Steelant- Travelling the Skies at High Speed - 2011
Hypersonic design: the challenge

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 procedures with respect to aerodynamic and propulsion.

A multi-disciplinary approach is actually needed to reach a global optimization.

This innovative approach is based upon the integration of a highly efficient propulsion unit with a high-lifting vehicle concept.
minimize kinetic jet losses while striving to the best uniformity but minimal induced velocity for lift creation.
Hypersonic design: the challenge
How a Hypersonic Aircraft may impact on the Environment?

- Noise at take-off and transonic
- Particle emissions
- Shock waves acoustic disturbance

Mach effect on the sonic boom for a given dynamic pressure
How the Environment may impact on a Hypersonic Aircraft?

- The physical environment surrounding the aircraft affects the aircraft design

Main parameter: Cruise Mach Number

Select a Mach Number

Different design concepts
How the Environment may impact on a Hypersonic Aircraft Design Process?

(example taken from ATLLAS, EU funded Research Program)

Sonic boom prediction for the studied vehicles in ATLLAS-I revealed similar levels as for Concorde but could eventually be alleviated by increasing the rise time, which transforms the boom into more of a puff. This encouraging path is then embedded into the design.

Aside from the cruise-induced sonic boom, the acceleration from subsonic speed ($M < 1.0$) to cruise speed ($M = 5$ to $6$) also leads to the creation of a zone of sonic boom amplification due to ray convergence. And atmospheric turbulence is known to strongly modify the shock fronts of the sonic boom.

Emission goals set by the EC could be achieved by the use of alternative fuels, such as methane or a CH4/H2-mix, having the potential to reduce carbon dioxide and particle emissions and thereby limiting the influence of hypersonic aircraft on atmospheric composition. On the other hand the essential high-combustion temperatures (regardless of fuel type) still make a reduction in NOx emission a challenge.
Dimension the fleet size

- **Civil market driving factor:** Premium Passengers (First & Business Class) on Long Distance Routes
# Civil Hypersonic Vs Mil. Hypersonic

## Market Drivers for Civil Hypersonic Aerial Systems

- Very Long Distance Routes
- (i) airline premium passengers (hypers.airliners)
- (ii) VIP transport (hypers.bizjets)

## Resulting Features of Civil Hypersonic Aerial Systems

- Mission Profiles (example Antipodal Hypersonic Transport) & payload requirements lead to big size (high TOW) design concepts
- high complexity, at Transport System level, for operations and logistics to be managed and kept within acceptable boundaries (consider for example management and logistic issues related to cryogenic fuels)
- risk of a big Environmental footprint
### Military Roles for Hypersonic Aerial Systems

- **(i)** strategic bomber = ultra-stealthy, supersonic, possibly hypersonic, ultra long-range, heavy-payload with unmanned-capability, so hypersonic is one of the options to be considered
- **(ii)** strategic strike = fast delivery of the payload on the target..need for unmanned long range strike
- **(iii)** Strategic reconnaissance = SR-71 legacy...
- **(iv)** Plans for Next Generations Aircrafts to be multi-role with intelligence, surveillance, and reconnaissance (ISR) capabilities.
- **(v)** More in general: Weapon Systems delivering P/L at long distance in a short time

### Resulting Features of Military Hypersonic Aerial Systems

- Options for Military Hypersonic Aerial Systems are more diversified, unmanned designs appear to be preferable
- operations, system level complexity & logistic issues may be even harder to solve in a framework of decreasing budget and increasing environmental constraints
- requirements may lead to medium or large size design concepts
- high complexity at Transport System level for operations and logistics to be managed and kept within acceptable boundaries (consider for example management and logistic issues related to cryogenic fuels)
- risk of a non sustainable Environmental footprint
ZEHST stands for Zero Emission High Speed Transport, thus emphasizing the will to take into account environmental footprint while designing the vehicle and its trajectory.

The 3-propulsion-system concept comprises turbofans for subsonic operations, rocket engines to cross the transonic regime and ramjet engines for efficient high-speed cruise.

see S. Defoort et al. ZEHST: environmental challenges for hypersonic passenger transport
Hypersonic - further greening tools: ZEHST project example
Mitigation of particle emission effects

At cruising speed and altitude, the ramjet propulsion system is operating and is likely to produce water and NOx particles.

Use of non-carbon hydrogen fuel to limit the production of NO by avoiding the formation of prompt NO.

But it is not sufficient to lower enough the production of NO. For transonic combustion at least a staged or multipoint injection scheme would be necessary.
Hypersonic - further greening tools: ZEHST project example

Mitigation of sonic boom effects

Shock waves are created at the nose/leading edge of the body, then at the wake after expansion along the body.

The pressure disturbances propagate mainly perpendicular to the Mach cone ($\alpha = \sin(1/M)$). At a reasonable distance of the body the pressure signal exhibits a N shape defined by $T$ and $\Delta P$.

The longitudinal volume and lift repartition are the two main drivers of the signal amplitude and time.

The N-shaped wave can be computed using the evolution of areas intersected by a section in the Mach angle direction (known as the "area rule"). For non axisymmetric bodies, this theory can be extended to take into account the repartition of lift.
Mitigation of sonic boom effects
Parametric studies show the effect of Mach number for a given dynamic pressure. Below the corresponding N-shape wave on ground, taking into account volume, lift and altitude effects.
Hypersonic - further greening tools: trajectory shaping

- **NOx emissions**: optimization depending on the ramjet design (cruise point only or extended)

- **Sonic boom**: climbing profile, transonic altitude, cruise altitude

- **Rocket noise**: effect of slope, thrust level, speed, altitude on footprints on the ground

- **Contrails**: effect of fuel, cruise altitude, geographic location, ...

- **Low speed**: turbofans integration, fuel selection
Green hypersonic concept(s)

GUIDELINES

- Anticipate on new specific regulations and maximize public acceptance likelihood
- Select adequate fuel towards the production of greenhouse gases
- Build up parametric tools that can be used at a conceptual design level
Franco Persiani
Chair Design Methods of the Aerospace Industry
University of Bologna
franco.persiani@unibo.it

www.unibo.it