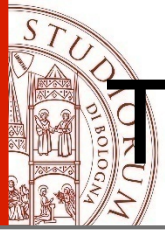


Environmental Protection

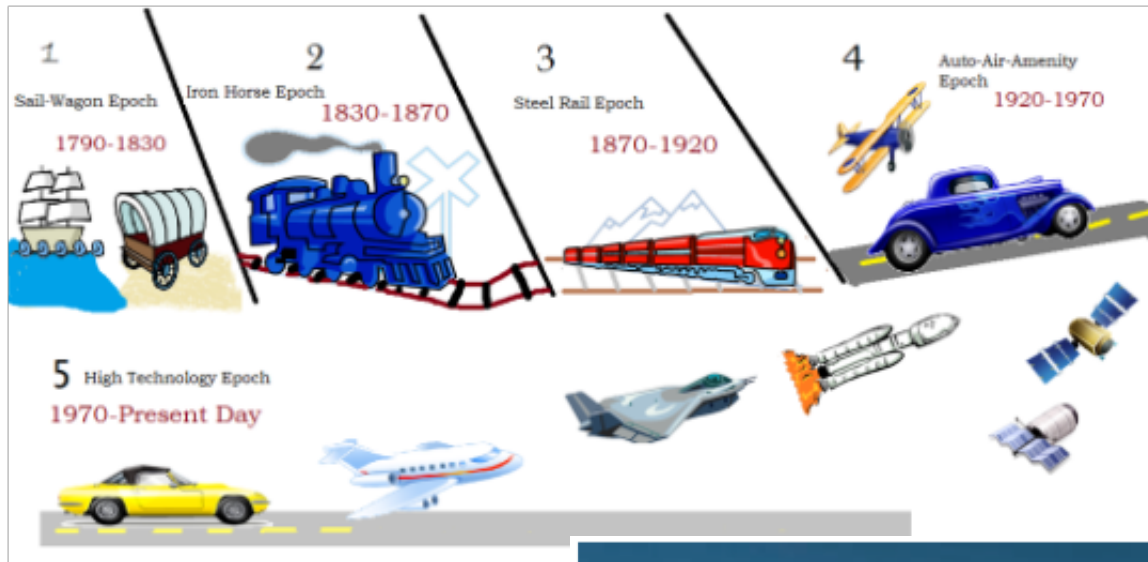
Franco Persiani, Università di Bologna

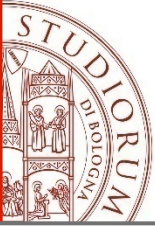
*Hypersonic from 100.000 to 400.000 ft
First Symposium on Hypersonic Flight*

Rome, June 30th - July 1st 2014



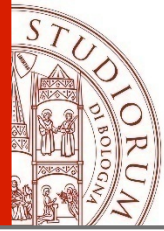
Transportation system evolution



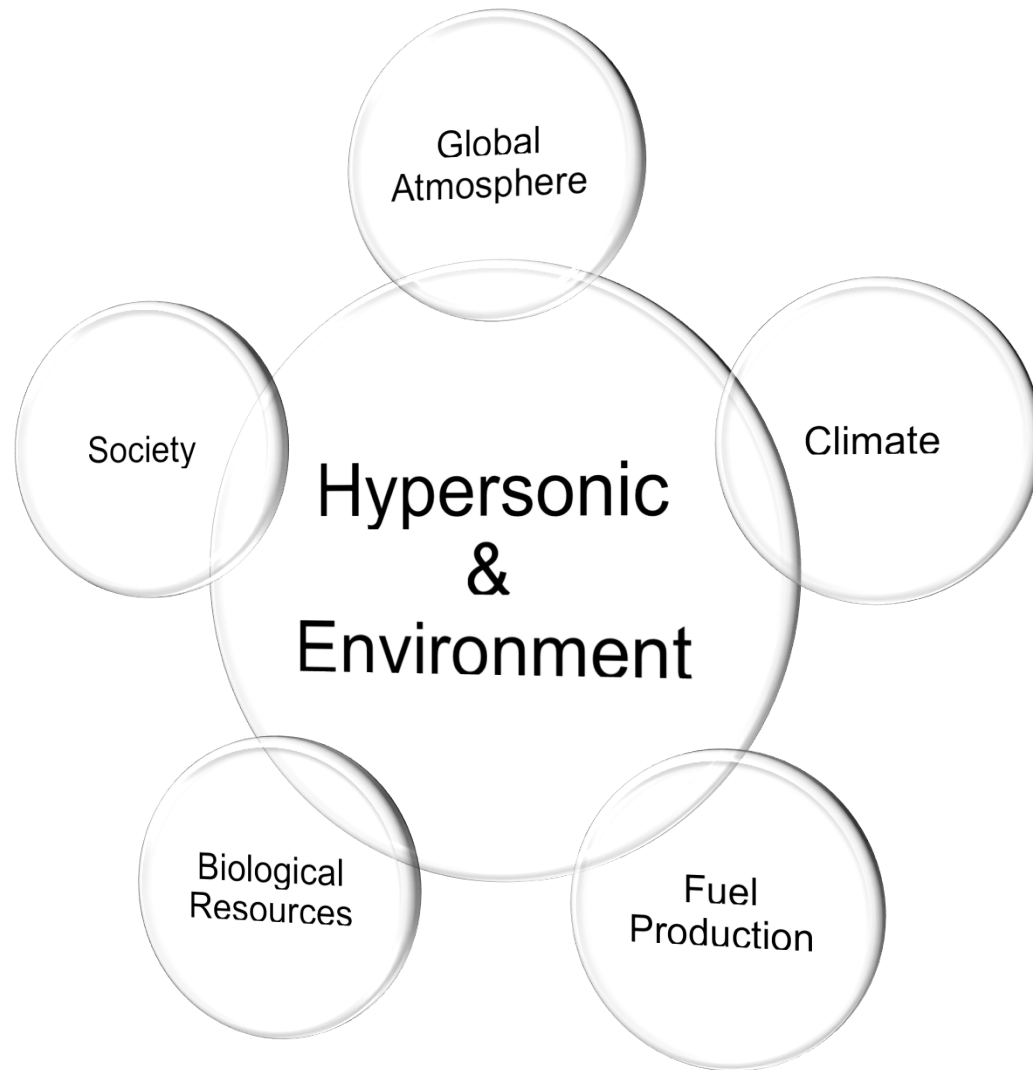


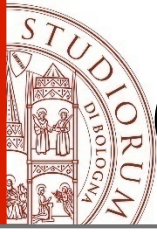
Transportation system evolution: some arising questions

- 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

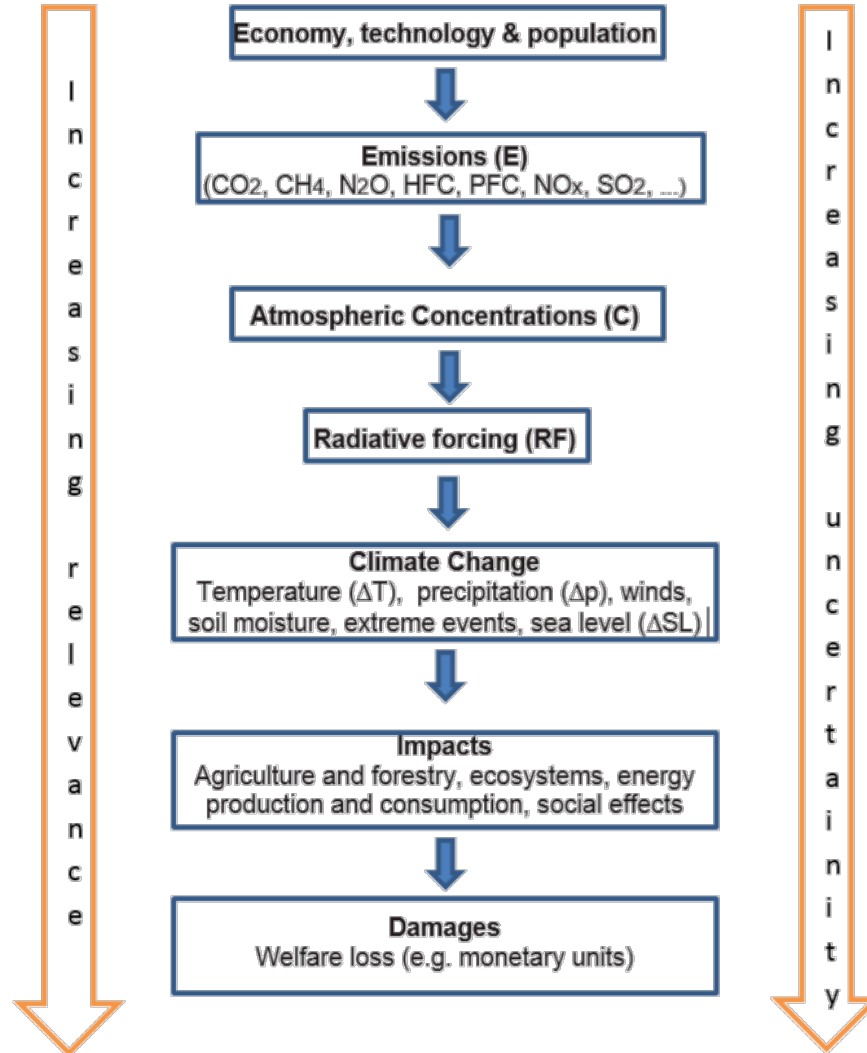


Hypersonic & Environment

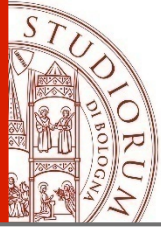




Chain of influences on climate



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

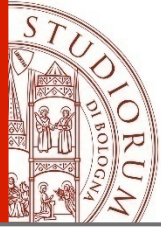


Atmospheric Chemistry of Aviation Emissions

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.

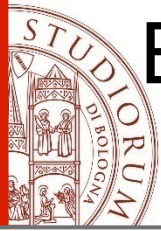
Emissions from aircraft are responsible for other atmospheric chemical processes that also have atmospheric warming consequences.

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

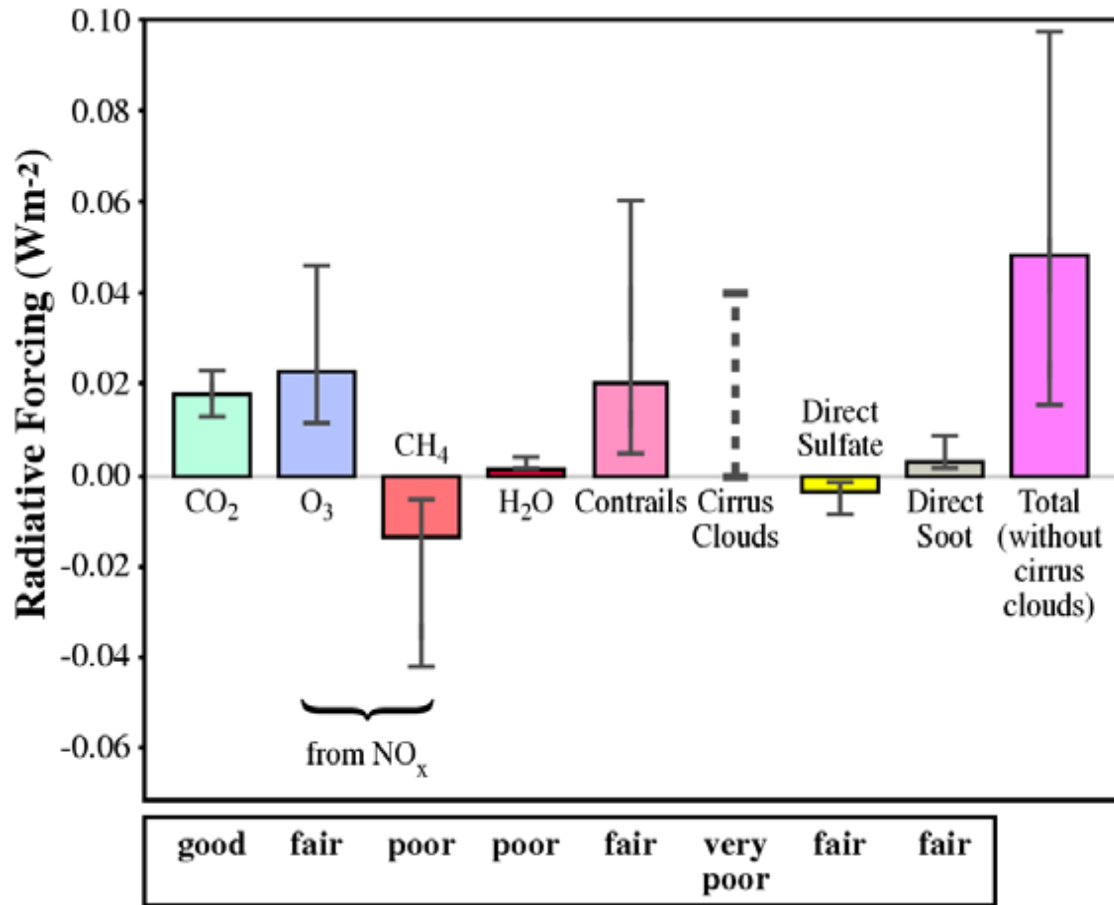


Atmospheric Chemistry of Aviation Emissions

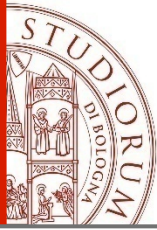
- Combustion of fuel in airplane engines results in emissions of **carbon dioxide (CO₂)** and **nitrogen oxides, (termed NO_x)**, as well as **water vapour and particulates**.
- **It is the emission of NO_x, water vapour and particulates at altitude that account for the extra impacts of aviation emissions.**
- 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

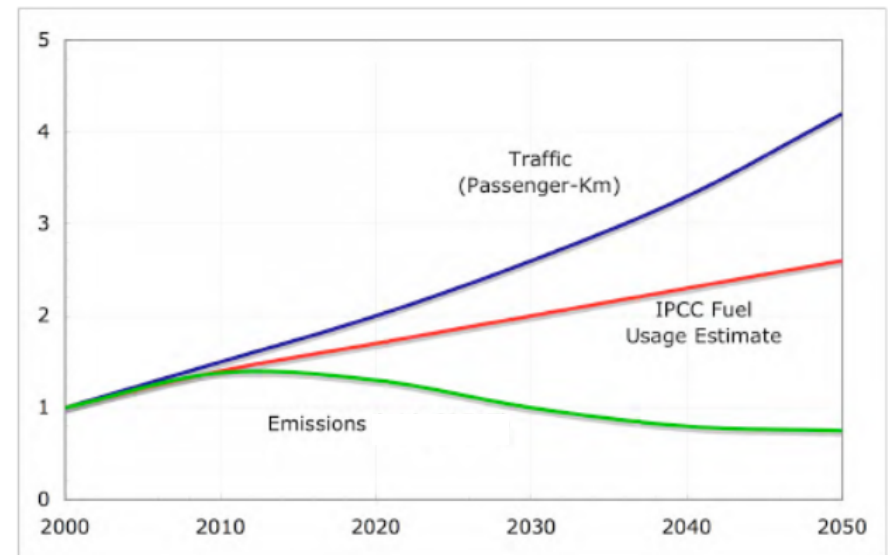
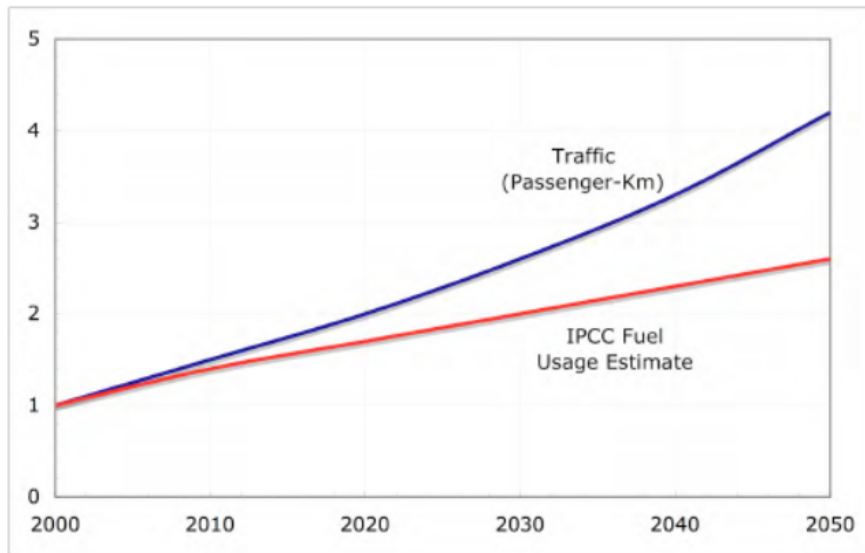


Report of the Environmental Change Institute - University of Oxford - C.N.Jardine 2005

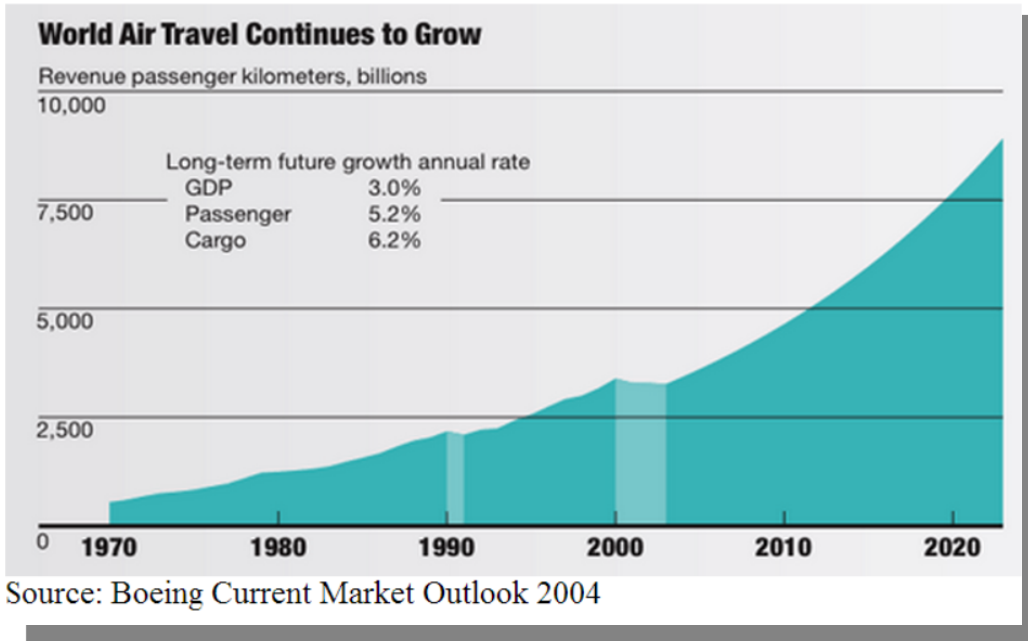


Air Transport Sustainability

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.

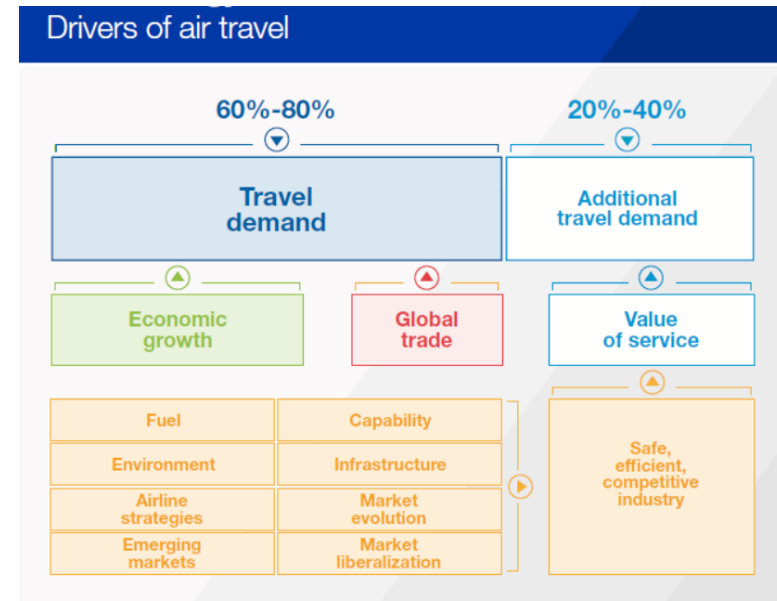


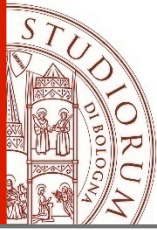
New transportation system



- Any new transportation system integrates **environmental** issues

- The introduction of a new transportation system can influence the transportation demand itself.
- Innovations in competing technologies may threaten the development of a new transp. system





Hypersonic design: the challenge

R Cruise Range [m] Breguet eq.
$$R = \frac{H}{g} \eta \frac{L}{D} \ln \left[\frac{1}{1 - W_F/W} \right] = \frac{V_\infty}{g \text{ sfc}} \frac{L}{D} \ln \left[\frac{1}{1 - W_F/W} \right]$$

g gravity constant [m/s²]

sfc specific fuel consumption [kg/s/N]

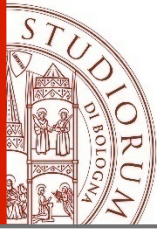
V flight velocity [m/s]

W total take-off mass [kg]

W_F fuel mass [kg]

overall installed engine efficiency
$$\eta = \frac{T \cdot V_\infty}{m_f' H} = \frac{V_\infty}{\text{sfc} H}$$

H the fuel energy content [J/kg]: 120 (LHV) and 142 (HHV) MJ/kg for H₂, 43.5 (LHV) and 47MJ/kg (HHV) for kerosene, 50.0 (LHV) and 55.5MJ/kg (HHV) for Methane
Increases with a factor of 2.7 by switching from kerosene to hydrogen



Hypersonic design: the challenge

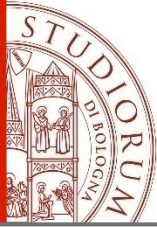
Aerodynamic L/D barrier and overall installed engine efficiency in function of flight Mach number.

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

L/Dmax and overall installed max engine efficiency have reverse dependencies on flight Mach number and their product η 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_u .

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.

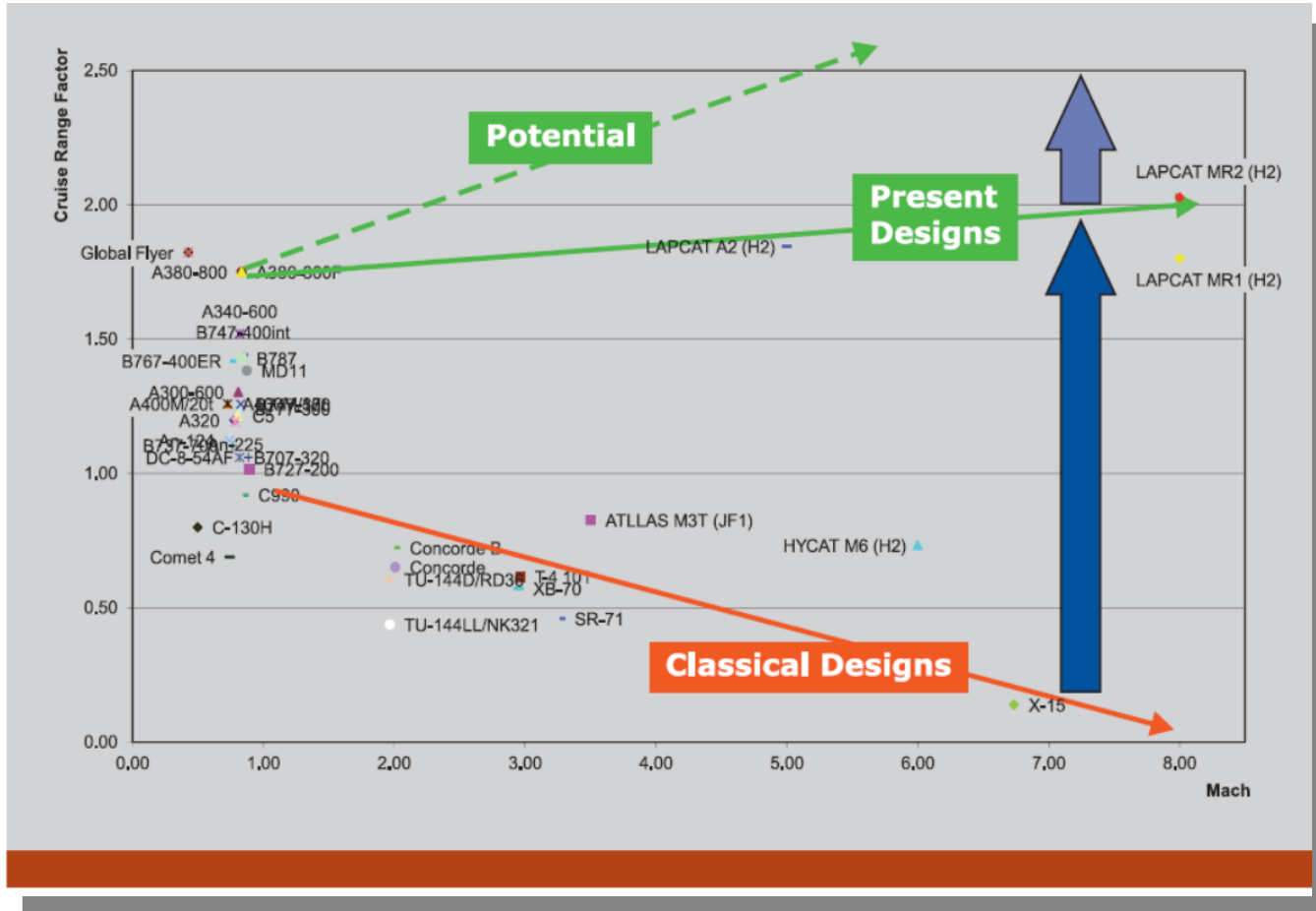
Classical approaches rely on separate and dedicated optimization design procedures with respect to aerodynamic and propulsion.

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.

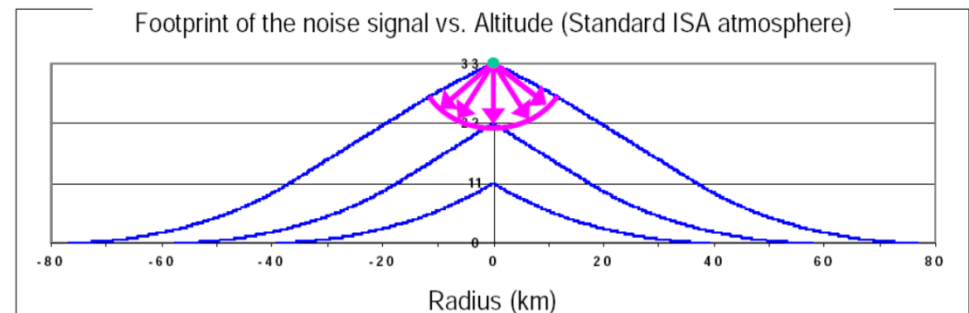
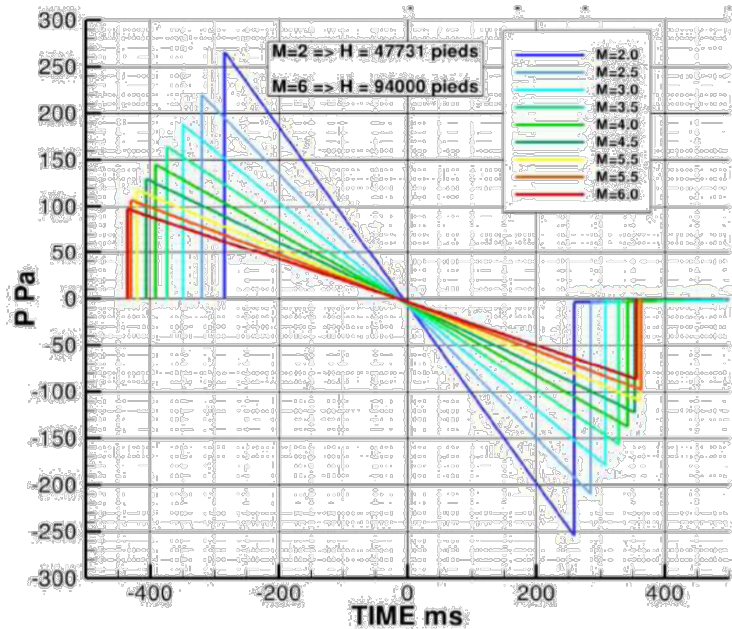
minimize kinetic jet losses while striving to the best uniformity but minimal induced velocity for lift creation

Hypersonic design: the challenge



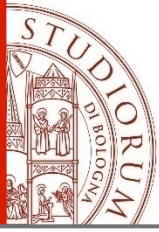
How a Hypersonic Aircraft may impact on the Environment?

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



effect of altitude on the ground footprint

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

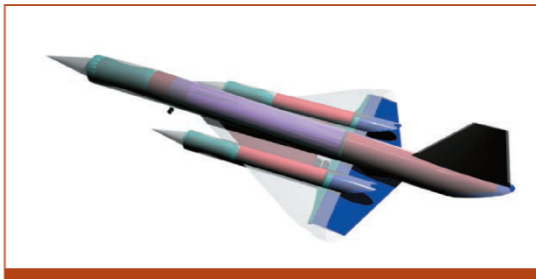
Main parameter: Cruise Mach Number

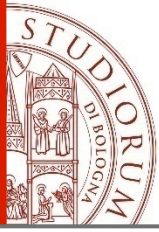


Select a Mach Number



Different design concepts





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

(example taken from ATLLAS, EU funded Research Program)

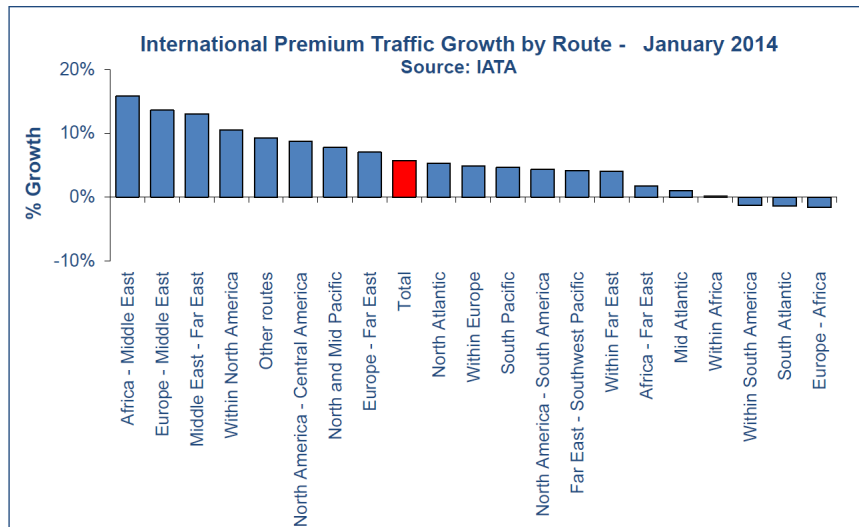
Sonic boom prediction for the studied vehicles in ATLLAS-I revealed similar levels as for Concorde but could eventually be alleviated by increasing the rise time, which transforms the boom into more of a puff. This encouraging path is then embedded into the design.

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 CH_4/H_2 -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 NO_x 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



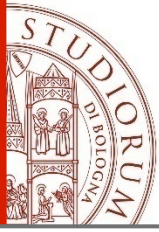
Civil Hypersonic Vs Mil. Hypersonic

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

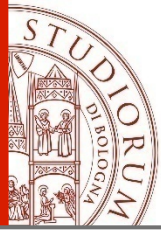


Hypersonic - further greening tools: ZEHST project example

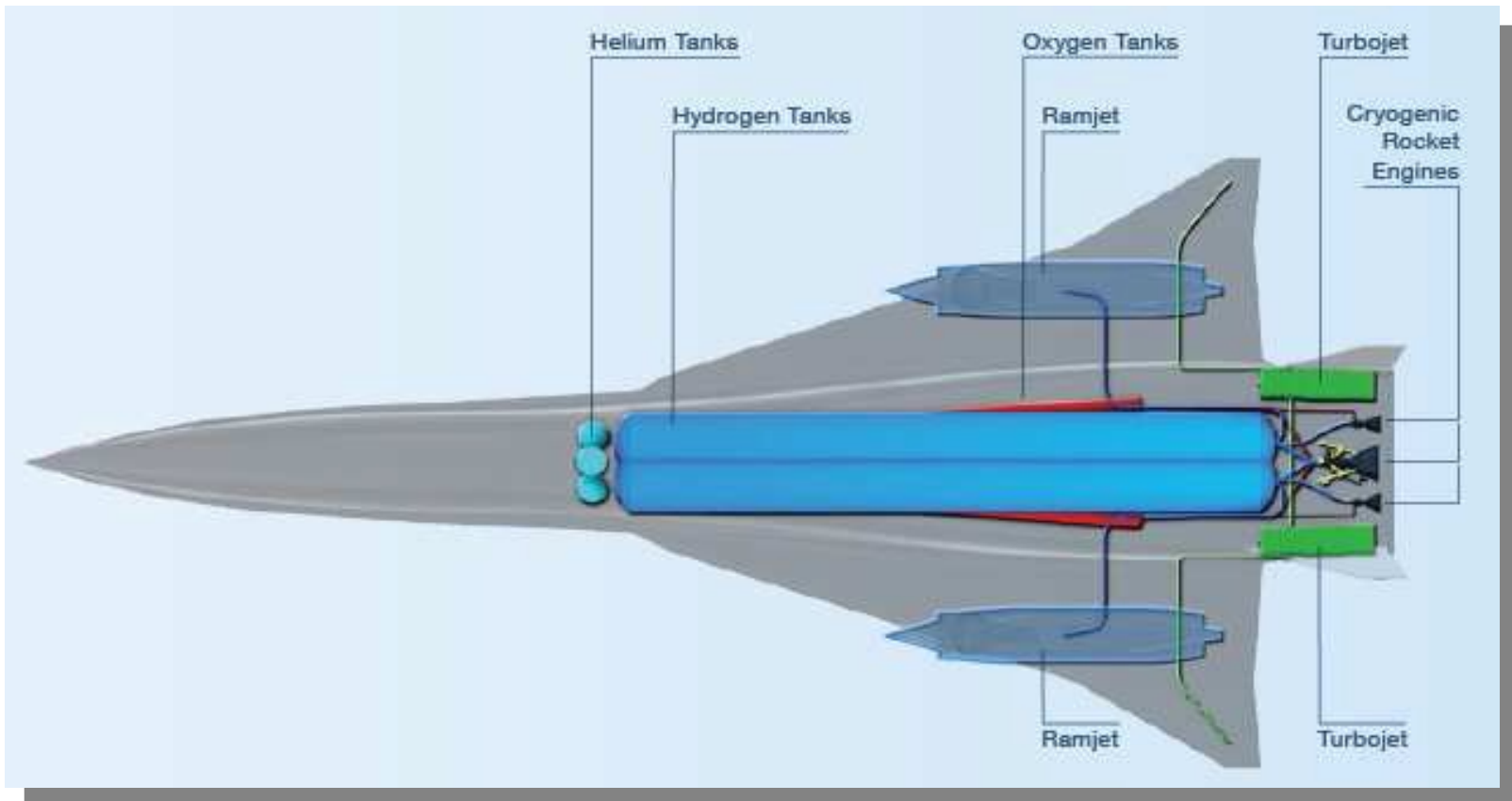
ZEHST stands for Zero Emission High Speed Transport, thus emphasizing the will to take into account environmental footprint while designing the vehicle and its trajectory

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





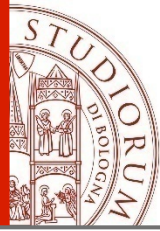
Hypersonic - further greening tools: ZEHST project example

Mitigation of particle emission effects

At cruising speed and altitude, the ramjet propulsion system is operating and is likely to produce water and NO_x 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 ($\alpha = \arcsin(1/M)$). At a reasonable distance of the body the pressure signal exhibits a N shape defined by T and ΔP

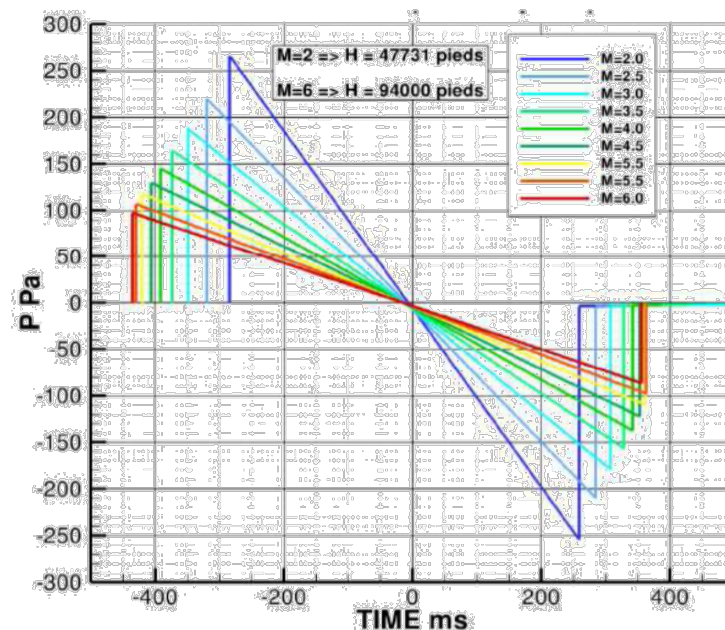
The longitudinal volume and lift repartition are the two main drivers of the signal amplitude and time.

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.

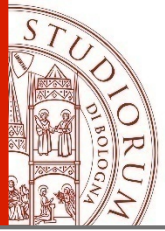
Hypersonic - further greening tools: ZEHST project example

Mitigation of sonic boom effects

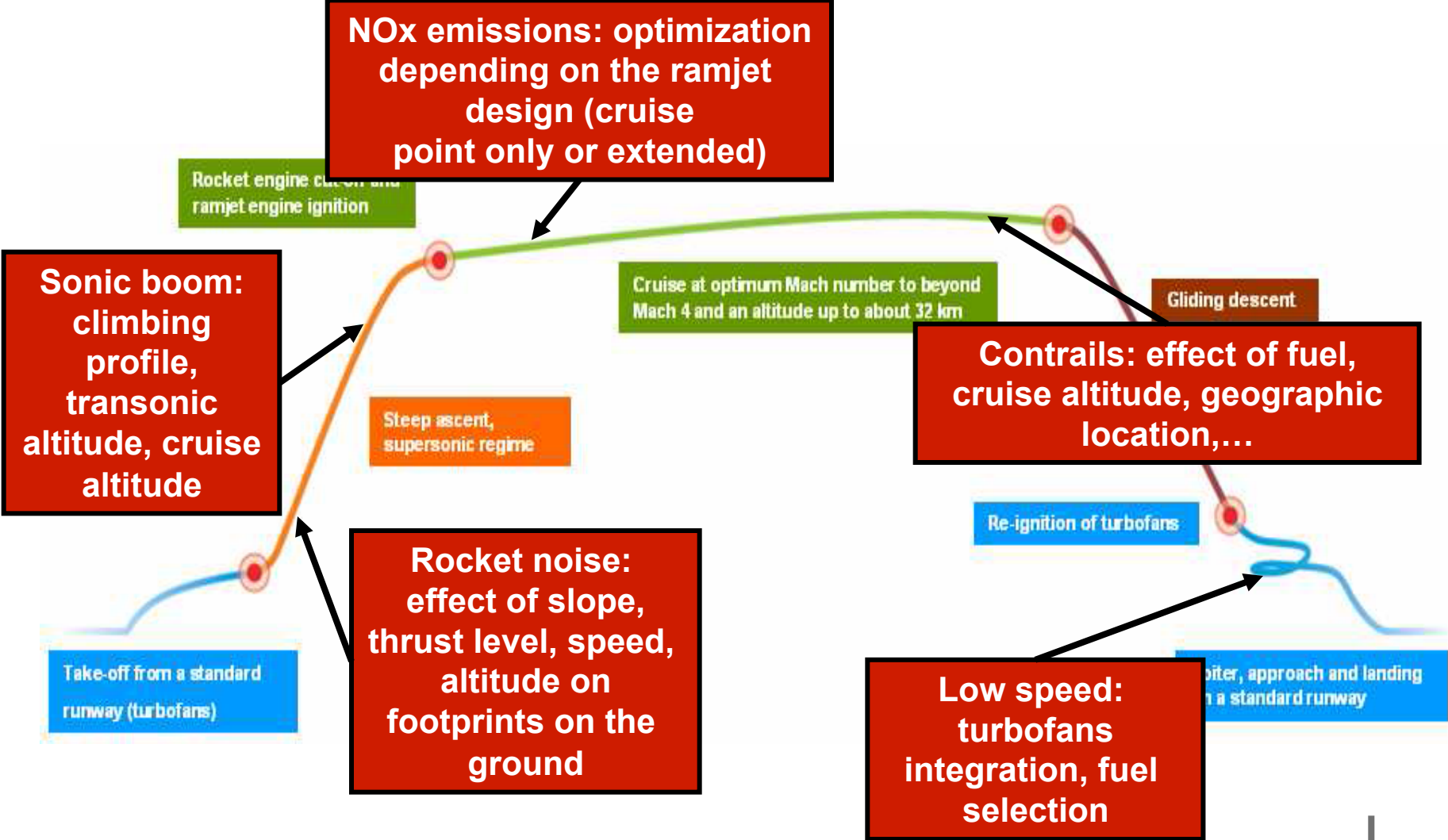
Parametric studies show the effect of Mach number for a given dynamic pressure. Below the corresponding N-shape wave on ground, taking into account volume, lift and altitude effects.



Mach effect on the sonic boom for a given dynamic pressure



Hypersonic - further greening tools: trajectory shaping

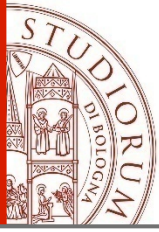


Green hypersonic concept(s)



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



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