From Air Transport System 2050 Vision to Planning for Research and Innovation

EREA

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This report addresses the research needed to pave the way for the Air Transport System 2050. It attempts to answer the question: "what can research establishments contribute to a comprehensive long-term, strategic process of innovation which will ensure Europe is a prime contributor to the aviation world of 2050"?

Key messages

- Major innovation will be possible only through a fully integrated research process between research establishments and industry.
- All promising technologies and drivers must be investigated; future technology selection must not be done too early.
- Research establishments have a key role in the certification and standardization of innovative technologies.
- Ground infrastructure and intermodality must become major fields of investigation in addition to all of the aeronautical domains historically studied by research establishments.

50 research scientists from
CIRA, DLR, ILOT, INCAS, INTA, NLR, ONERA
contributed to the study 50% co-financed by EREA

Content

WHAT RESEARCH FOR THE FUTURE OF AIR TRANSPORT SYSTEM IN 2050 ?

What research is needed to pave the way for the future of Air Transport System in 2050? This is the question EREA tried to answer to define its research agenda. Two studies were launched to attempt to answer it.

- The first: **EREA: vision for the future –Towards the future generation of Air Transport System,** published in 2010, investigated four 2050 aviation scenarios, describing the associated technology challenges and choices as well as recommendations where more research is needed.

- In the second, these recommendations were included in the goals set out in the European Commission report of the High Level Group on Aviation Research: **"Flightpath 2050: Europe's Vision for Aviation"** published in 2011.

This report presents the conclusions of the second study.

Flightpath 2050 : Europe's Vision for Aviation

In 2011, key European aviation stakeholders from the aeronautics industry, air traffic management, airports, airlines, energy providers and the research community were invited to come together in a High Level Group to develop a vision for Europe's aviation system and industry.

Goals for a sustainable approach to aviation in 2050 : Protecting the environment and the energy supply *(Flightpath 2050: Europe's Vision for Aviation)*

- Technologies and new procedures will bring a 75% reduction in CO2 emissions per passenger-kilometre and a 90% reduction in NOX emissions. The perceived noise emission of flying aircraft is reduced by 65% relative to typical new aircraft in 2000.

- Aircraft are emissions-free when taxiing.

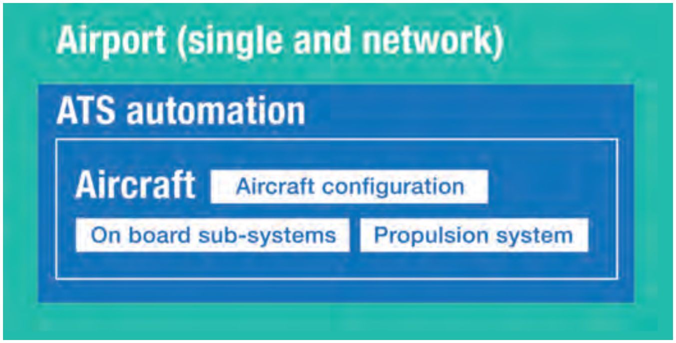
- Air vehicles are designed and manufactured to be recyclable.

- Europe is established as a centre of excellence on sustainable alternative fuels, including those for aviation, based on a strong European energy policy.

- Europe is at the forefront of atmospheric research and takes the lead in the formulation of a prioritised environmental action plan and establishment of global environmental standards.

Priority Research Areas

Five priority research areas (see figure below) have been selected for research that aim to keep Europe at the forefront of aviation design, manufacturing and operation - particularly in the area of environmental sustainability:



Vehicle Configuration

Changing the shape of aircraft to go far beyond current conventional configurations performance is becoming possible because of advances in materials, computational power and design techniques. The result will be major improvements in aerodynamic efficiency leading to much lower fuel consumption and therefore pollution.

Propulsion

Propulsion ranks alongside aircraft configuration as the major game-changing area of aviation in terms of improving its environmental performance. This section looks at technologies based on classical engines and also at potentially revolutionary concepts such as Intercooled systems, Nanotechnology, Rotating Detonation Engine, Pulse Detonation Engine and Piston engine injection technology. Sustainable alternative fuels such as non-biofuels, biofuels, hydrogen are examined and the nuclear energy issue is also considered for the propulsion.

On Board Subsystems

Ever more numerous and complex onboard functions will be carried out by software rather than hardware, because of weight and volume constraints. Other major advances are likely in the provision of energy to the aircraft, advanced health monitoring and prognostics and adaptive, multi-purpose hardware able to implement different tasks depending on the flight phase.

Towards Full Automation?

Automation already features in many safety-critical aviation activities. The report highlights three main areas in which automation will be increasingly evident: the four-dimensional contract, air traffic management and aircraft.

Airport

The airport is at the heart of the aviation system and improvements in intermodality and infrastructure will have positive results throughout the network. Movements of vehicles on the ground will be automated and integrated, optimised, intermodal transport systems provided, further improving the passenger experience.

Detailed descriptions of each priority research area are presented on following pages.


CO2 reduction
NOx reduction
Perceived noise reduction
Drag reduction
Mass reduction

VEHICLE CONFIGURATIONS

Vehicle configurations : shaping the future

The configuration of civil aircraft has evolved little since the 1920s. Almost without exception, passengers have been transported in a tubular fuselage, with the empennage at the rear and the engines mounted either under the wings, or at the rear. Although major advances in aerodynamics and flight control systems have contributed greatly to improving the performance of the classic configuration, the advent of new design materials and design processes, along with a far better understanding of the aerodynamic and structural interactions that occur in different phases of flight, are driving some radical ideas for the future.

It is now therefore possible to consider some of the enabling technologies needed for revolutionary configurations and identify potential technical solutions and their integration within the overall air transportation system. Since these perspectives and their related technologies are closely linked, a system integration-oriented approach must be taken. Whether they are single subsystem technologies or completely new aircraft configurations, studies must always consider integration with different levels of the air transport system.
The following chapter highlights some promising aircraft configurations and different single aircraft technologies which might contribute to the Flightpath 2050 challenges.

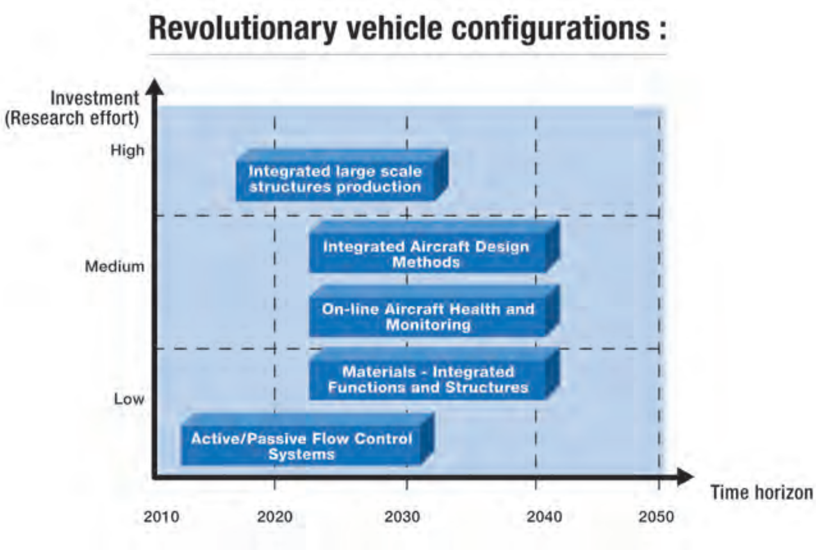
Recommendations

On the *single aircraft technology level* it is recommended that research be carried out on active/passive flow control systems to further improve aerodynamic efficiency and compatible high-lift devices.

Further emphasis concerning *materials and structures* should be given to
- Material-oriented design methods
- Integrated structures and integrated functions and structures (e.g. integrated sensors and antennas

On the *overall aircraft level* research should focus on:
- Integrated aircraft health and usage monitoring systems covering structures as well as systems to increase safety by flight envelope protection, aircraft reconfiguration and on-condition maintenance capabilities

The following chart shows the different technologies comparatively based on the level of investment required (low, medium and high), as a function of time (2015, 2025 and 2050)

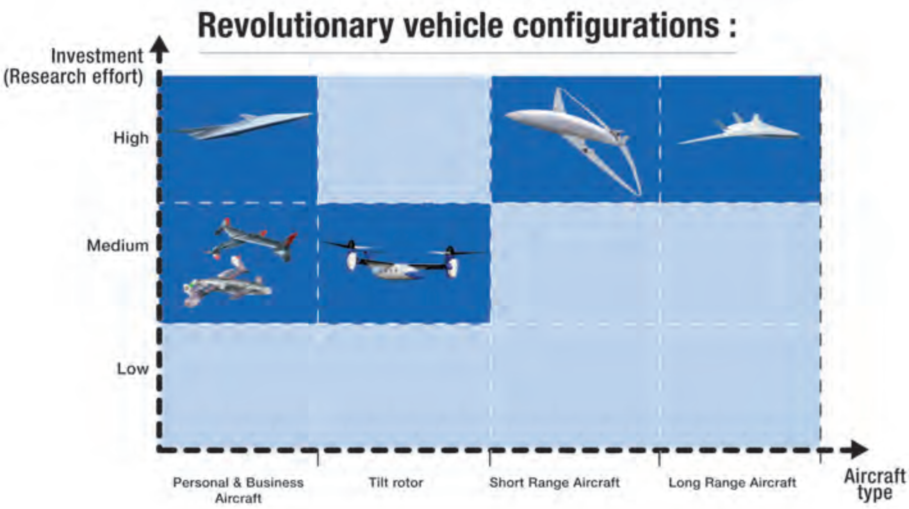


Regarding **aircraft configurations** priority should be given to:

- Development of integrated and interdisciplinary functional aircraft design methods, including systems, software and integration aspects considered from the conceptual design phase
- Integrated blended wing body and tail-mounted open rotor concepts
- Aircraft configurations with regard to type of energy (e.g. hydrogen, electrical engine…)

Efficient aircraft production is of paramount importance for the success of the European aircraft manufacturing and systems industry. Therefore **efficient mass production of large, integrated, complex CFRP/metallic aircraft structures** must be developed by addressing highly automated production tools and production-oriented design.
Finally it is strongly recommended that there should be higher priority on **overall integrated air transportation design methods,** with the aircraft as the prime focus but taking all main air transportation substructures and their interfaces into account.

The following chart shows the different types of aircraft based on the level of investment required (low, medium and high), as a function of time (2015, 2025 and 2050)



Aircraft Configurations

We present five aircraft configurations: the Blended Wing Body and Prandtl wing are potential solutions for commercial transports, while advanced tilt-rotors will improve access to city centres and offshore platforms. Finally, personal aircraft and supersonic transports are assessed.

Blended Wing Body

Today's classical aircraft configurations feature separate structures for providing lift (wings) and carrying the payload (fuselage). This results in a heavier structure, additional wetted surface and associated viscous drag. The flying wing configuration is recognized as the most efficient aerodynamic solution, but presents challenges in many other areas. The blended wing body (BWB) presents a good compromise. Its higher structural complexity could be mitigated with development of advanced composite materials and production processes.

The BWB also provides good potential for larger, more comfortable passenger cabins and new storage solutions for baggage, cargo and fuel. The operation of such aircraft at so-called Mega Hubs will present operational challenges, however, affecting the design of the aircraft regarding emission-free taxiing, geometry, service access points and boarding arrangements.

Prandtl Plane Concept
For a given wing span and lift, the Prandtl-type biplane, with wings connected at the tip, provides a theoretical induced drag reduction of about 20% during low-speed phases such as take off, climb, descent and landing. Such a configuration might be an interesting solution for short take-off and landing short-range aircraft with less range than today's Airbus A320 or Boeing 737.

The potential benefit of this radical change in configuration might be a reduction of up to 10% in fuel burn, as long as weight is not increased compared to a conventional aircraft. This concept provides also new solutions for engine integration.

Tilt-rotor aircraft
Tilt-rotors combine the hover advantages of helicopters with the higher-speeds of turboprop aircraft, overcoming the problem of helicopter speed being limited by the loss of main rotor efficiency at higher forward speeds.

The next generation of tilt-rotors will feature a partially tilted wing to improve rotor efficiency at hover. A 20-passenger aircraft would have higher range than the BA609 at a cruise speed of around Mach 0.5 - close to that of modern turboprop aircraft. Depending on the regulatory situation, civil tilt-rotors would operate as commuters between medium/large cities and for offshore oil & gas plants, or long-range strategic-air reconnaissance applications.

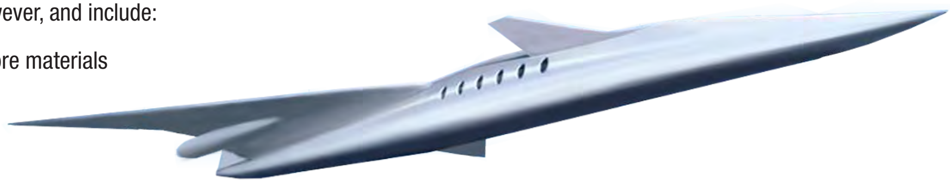
Personal Air Transport
For personal air transport, short-range small aircraft provide the lowest emissions and easiest handling. Such aircraft would be operating along with others at lower altitudes and speeds. An aircraft with up to eight seats could be powered by an electric main engine and have all-electric systems. High levels of automation and pilot assistance would be required.

The characteristics of such aircraft are reduced acquisition cost, reduced weight, reduced fuel consumption, increased reliability, reduced support equipment, simpler maintenance, expanded flight envelope, and improved survivability. The concept requires the resolution of a number of major technology issues, however, including electromechanical actuators, environmental control and ice protection systems, and engine technology.

Supersonic business transport
Linking the growing business metropolises in North America as well as in Europe, Asia and South America with supersonic business aircraft could provide a more realistic business case than charter and scheduled travel.

Significant technological challenges remain, however, and include:

- Development of high temperature carbon fibre materials
- Sonic boom noise control
- Easy to handle, reliable aircraft
- Low-emission, high-speed propulsion



Key technologies for new configurations

Drag Reduction

Vortex-induced drag
Aircraft deflect air downwards for lift generation, causing vortex-induced drag, which is typically responsible for around a third of total cruise drag for transport aircraft. Ways of reducing it include:

Increased wingspan
Wingspan is the main parameter controlling vortex-induced drag. Slender, high-span wings (i.e. high aspect ratio) generate less vortex-induced drag, but may result in a heavier wing structure. Early jet transports favoured wing aspect ratios of around 8.
This requires stronger structures to carry the resulting bending and torsional moments without increasing the structural mass.
Tuning spanwise lift distribution with movable trailing-edge devices is promising.
There could be a potential 10% fuel burn improvement if airport terminal layouts allowed for increased wingspan in future aircraft configurations, but this should be balanced against increased aircraft mass and operational flexibility.

Wingtip Devices
The right choice of wingtip device and its integration into the aircraft is a key research area. The aim is to maximise efficiency in cruise, where drag reduction is crucial. Winglets are the most popular wingtip device, and are already in used on some aircraft. Other designs include the wing grid, wingtip sails and spiroid, as well as the wingtip turbine, which can recover some of the energy losses caused by vortex-dependent drag and use it to drive a generator. Wingtip devices could bring cruise fuel savings of up to 10%.

Viscous Drag reduction

Viscous Drag accounts for around two-thirds of total drag and is comprised of friction drag and viscous pressure, or form drag. This is currently a main area of research as potentially major efficiency savings can be made.

Wetted Surface Area
Vertical tailplanes are sized for ensuring lateral stability, crosswind landings and complying with one engine-inoperative safety requirements. For modern fly-by-wire aircraft lateral stability can be relaxed and sizing becomes dependent on the one-engine-out scenario.

Double-hinged rudders can reduce tailplane area by as much as 15%, which might produce a 0.5% fuel burn reduction. This could be increased by passive or active flow control devices to further increase rudder efficiency.

Turbulent Boundary Layer Drag
Current transport aircraft achieve almost fully turbulent boundary layer flow over all wetted surfaces. Although the physics of fully turbulent flow is well understood, there are still opportunities to reduce turbulent boundary layer drag.

V-grooved riblets have shown substantial reductions in skin friction. Wind-tunnel and flight testing have indicated potential aircraft fuel burn savings of up to 2%. In-service trials revealed premature wear of riblet films, however - an area of continued research.

Controlling turbulent boundary layers with smart Micro-Electro-Mechanical-Devices (MEMs) on all surfaces holds real potential. A more detailed understanding of unsteady turbulent substructures and how to modify these actively to achieve drag reduction needs to be developed. Because experiments are very difficult to perform, pure aerodynamics research needs to be complemented by continued effort on technologies such as high-performance computing (HPC) for virtual simulations of new configurations.

Laminar flow

Laminar flow promises a potential 5% - 10% fuel burn reduction, with the benefits increasing the longer the aircraft is in cruise. While the aerodynamic principles are well understood, the production and operation of the extremely smooth surfaces presents challenges. Forward-swept wings are beneficial for achieving natural laminar flow at relatively high Mach numbers and can also help to prevent fuselage boundary layers from interfering with the wing leading edge flow.

Natural laminar flow can be applied to components with slightly swept leading edges, such as engine nacelles.

Hybrid laminar flow can be achieved by embedding perforated suction panels into the leading edges of highly-swept wings and tail surfaces for aircraft flying faster than Mach 0.7.

New structural technologies like morphing leading edges may enable the generation of lift at low speeds for take-off and landing with a laminar flow wing.

Other design options would reduce parasitic drag due to external roughness and wakes due to windscreen design, windscreen wipers, rain rims over doors, inlet and exhaust ducts, and door handles etc.

Noise reduction

Aircraft contribute to noise by their operational procedures, exposed installations and engine location. The magnitude of airframe noise is comparable with engine noise (fan and jet) during the approach and landing phases, and dominates when the aircraft is directly overhead.

The sources of airframe noise are:

- Flaps (trailing and side edges, slots)
- Leading edge slats
- Landing gears and wheel wells
- Wing and tails (trailing edge, tips)
- Fuselage (turbulent boundary layer)

Noise reduction on aircraft is interdisciplinary, involving various aircraft subsystems such as high-lift systems, landing gear and engines.

High-lift devices

High-lift devices are significant sources of noise.

Natural laminar flow wings imply fewer high-lift devices. One of the most promising technologies is to replace slotted flaps and slats by closed and smooth surfaces, but this would result in wings which do not produce the same lift as multi-element airfoils, so additional technologies like local flow-control devices will need to be developed to avoid flow separation.

Landing Gear

An advanced low-noise main landing gear might feature:

- Telescopic side-stay
- Streamlined leg door fairing
- Upstream installed torque link with fairing, no articulation link needed
- Bogie front fairing, brake fairing, hub caps and wheel/tyre rim in-fills

Weight reduction: a key driver for efficiency

Minimising aircraft weight is a key driver for efficient transportation, so technologies enabling this are of great interest. Within the ACARE Vision 2020 programme a potential overall mass reduction of 30% has been envisaged. However, single lightweight materials will not be sufficient to achieve such a challenging goal. More integrated interdisciplinary approaches will be needed such as:

- Integrated design
- Materials-related design and efficient local use of lightweight materials
- Production of large integrated panels
- Efficient assembly

Three principle directions can be derived from these opportunities:

- material-oriented design methods
- integration of different materials systems
- adequate production tools and procedures

…in parallel with the development of new materials and integrated structures.

Integrated structural design

Composite materials and manufacturing technologies allow for the design of more integrated structures with fewer fasteners, reducing weight. Other advantages compared to metals include fatigue damage resistance, corrosion resistance and thermal insulation.

The drawbacks of these materials are, in general, their sensitivity to impact, limited damage tolerance properties and low electrical conductance. Composites already represent up to 50% of the structural weight for the most modern commercial aircraft, such as the Boeing 787 and Airbus A350.

Aeroelastic tailoring

Aircraft wings are designed such that their shape yields optimum lift and load distribution, but these values vary as the wing is deformed during flight. Aeroelastic tailoring can generate wing designs that deflect under loading in such a way as to moderate the internal load increase. Composites are particularly useful for this type of design because, by orienting fibres in specific directions, the stiffness characteristics of the structure can be designed to give precisely the deformation response to the experienced loading to achieve the optimum wing shape.

Self-healing materials

A structurally-incorporated ability to repair damage caused by mechanical use over time. Current research on composite materials will expand the scientific understanding of self-healing materials and introduce the cradle-to-cradle concept for thermoset-based plastics and composites.

Material-related structural design

Life cycle assessment studies of environmental emissions have demonstrated the benefits of structural aircraft components made from lightweight CFRP in comparison to aluminium and Glass Laminate Aluminium Reinforced Epoxy (GLARE), expressed in fuel consumption and CO2 emissions and taking into account their “cradle-to-grave” emissions.

Besides increasing the amount of composites in the airframe structure, further weight and fuel burn reduction can also be achieved by further optimising current composite structures in terms of cost and performance.

Unconventional fibre lay-ups / elastic tailoring

Lighter composite structures can be obtained through improved local directional stiffness properties. This can be achieved by local elastic tailoring of structures using advanced fibre placement, in combination with advanced design, analysis and optimisation methods, including “as-manufactured” material details in the design loop.

Windowless cabin

Aircraft windows in the passenger cabin and cockpit contribute to weight and drag. A radical solution to reduce weight might be replacing the windows with lightweight low-power-consumption screens with passenger-selectable views. This technology would mean that unusual aircraft configurations such as BWBs and flying wings could be considered.

New materials

Composite materials have the potential to provide for the integration of components and other items such as antennas, sensors and actuators into the structure. In some areas, however, metallic structures are seen as more beneficial in terms of stiffness and producibility.

Thermoplastic composites

Most carbon fibre composites contain thermoset polymers (mainly epoxy) for the matrix material. To enhance damage tolerance and toughness, thermoplastic polymers can be used, which can be heated, melted or softened, reshaped, and then cooled to a final hardened shape, making them easy to rework and repair.

Nano-technologies for improved material properties

Further improvement of carbon fibre composites properties, in particular their brittleness and fracture sensitivity, can be achieved by nano material additives such as graphene platelets or carbon nanotubes. Strength, stiffness and resistance to fatigue crack propagation gains of several orders of magnitude have been demonstrated. Moreover, the significantly improved electrical conductivity of the composite materials overcomes the need for lightning strike protection systems usually achieved by copper or bronze meshes inserted in the laminate.

Interdisciplinary and integrative technologies

Production technologies: large integrated panels

Composite materials and their related manufacturing technologies provide technical and economical enablers for new aircraft configurations. Larger, integrated structural elements with curved shapes can be realized using carbon fibre reinforced plastics.

Although some experience has been achieved over the last 20-30 years, efficient production in terms of tooling and procedures remains to be developed. Automated fibre placement and filament winding has enabled advanced, economically viable manufacturing of composite material structures, but for one-shot composite components, the final assembly line process must be adapted to composite materials, which have less ductility and higher stiffness.

On-Line Aircraft Health and Usage Monitoring

Aircraft operational behaviour can be improved through efficient damage and fault detection, maintenance, and logistics. For this, real-time assessment of the composite structure by integrated strain monitoring systems, based on networks of fibre optic sensors, can be applied. A better understanding of structural behaviour during flight may lead to a reduction of drag losses by using strain readings to adjust deformation during flight or to improve the safety margins used in the design process. Strain readings from critical parts of the structure could monitor damage or damage growth during flight.

This information could be used to develop an integrated aircraft health and usage monitoring system, which enables the overall aircraft state to be assessed. Such a system would require high reliability, intelligent sensor data gathering, sensor fusion and analysis, and the development of appropriate action procedures.


BioFuel
Air

PROPULSION

Future propulsion: protecting the environment

The turbofan engines powering today's aircraft are approaching their optimum in terms of efficiency and only major changes in aircraft configuration and/or propulsion concepts will bring step changes in fuel burn and emissions.

While there is still plenty of scope for further improvements in turbofan technology, the major engine manufacturers and research institutions are working on a large set of radical solutions for the next generation of short/medium range transports, which account for most fuel consumption, and hence emissions. The attraction of major fuel savings is balanced, however, by significant challenges on noise, complexity and passenger acceptability.

Promising technologies

In the short term, continuing development of turbofans will continue to reduce fuel burn, noise and emissions. It is clear that a step-change will be required to achieve any further significant fuel burn improvement, and all of the engine manufacturers are looking at potential solutions, one of the principal research areas being contrarotating open rotors. Such engines are not seen as suitable for long-range aircraft, however, and geared fans and other approaches are being considered.

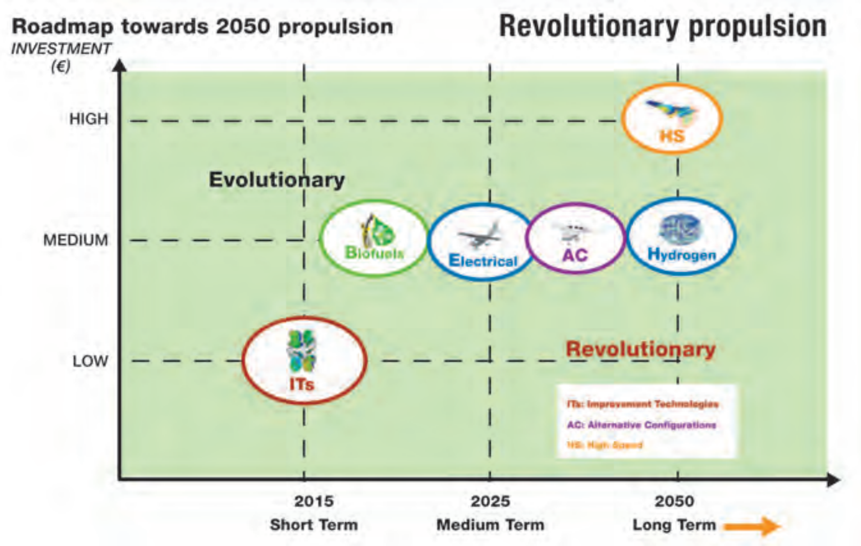
Electric propulsion of unmanned aerial vehicles and small aircraft is a real possibility in the **medium term.**

Sustainable alternative fuel concepts must become a priority for aeronautics.

Biofuels will contribute to emissions reductions and are already being evaluated in commercial transports. **For the longer term,** studies into emissions-free hydrogen fuel continue.

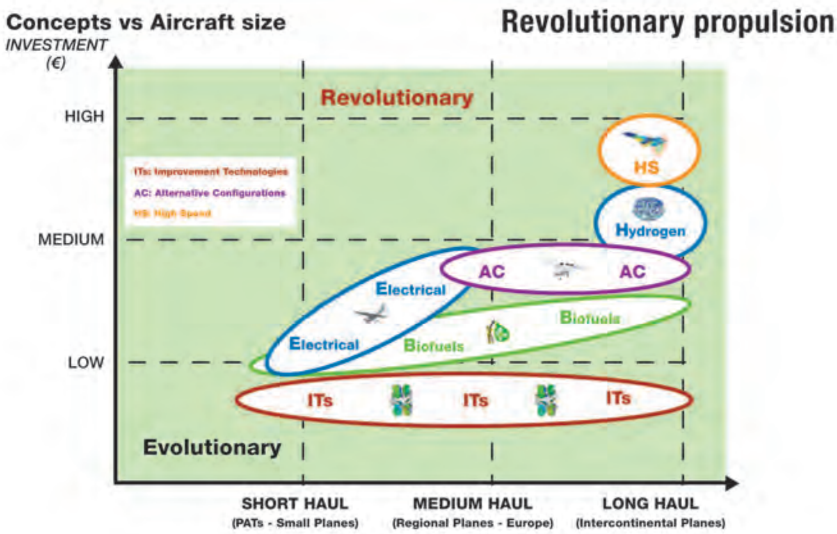
The following two charts compare the different technologies based

- on the level of investment required (low, medium and high) and as a function of time (2015, 2025 and 2050) and
- on the type of aircraft (Unmanned Air Vehicle, Personal and Commercial Transports).



Technologies versus Investment/Time

Technologies versus Investment/Aircraft Type



Technologies based on classical engines

Engine manufacturers are constantly working to improve engine efficiency. Work currently centres on raising the bypass ratio with new fan configurations, and improving the thermodynamic efficiency of the core. There is also much potential for improving the performance of aircraft piston engines.

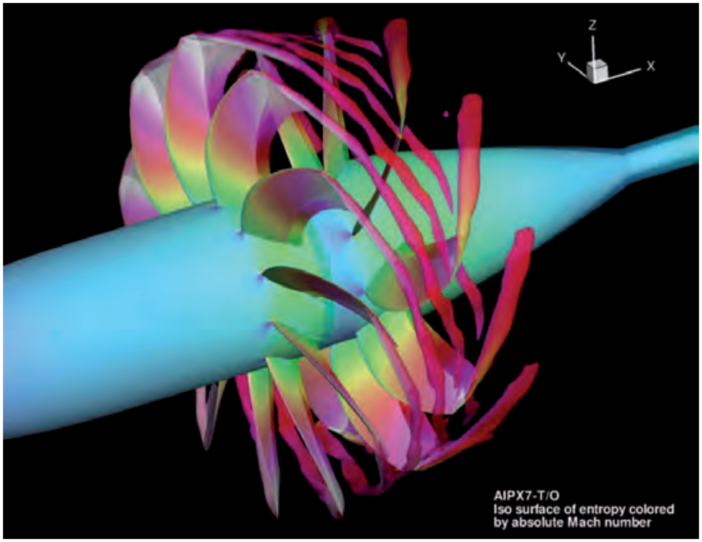
Contrarotating open rotor

Contrarotating propellers driven by an advanced core are mounted at the rear of the aircraft, offering up to 30% lower fuel consumption compared to the most advanced turbofans available today.

Because of their large diameter, open rotor engines have no fan cowlings. While saving weight and reducing drag, this removes an important noise-shielding device, so that other ways have to be found to reduce the noise caused by the interaction of the contra-rotating blades. Maximum cruise speeds are limited to Mach 0.8.

Contrarotating fan

Higher fan efficiency and reduced engine diameter reduce engine drag, reducing fuel burn and emissions. A dual-stage, statorless contrarotating fan replaces the single-stage fan and stators. The pressure rise across the fan is split between the two stages, reducing the number of blades per stage and allowing for higher axial flow Mach numbers, reducing fan (and therefore engine)



AIRBUS generic Open Rotor – CleanSky EU project diameter, engine and cowling weight, and drag. Alternatively the bypass ratio, and therefore propulsive efficiency, can be increased without increasing engine diameter compared to current engines. Fan efficiency is increased by 2-3% compared to conventional engines with geared or direct drive fans.

The fan generates higher noise because there is less space for acoustic treatment and a planetary fan drive system is necessary, which also adds weight and complexity.

Intercooled systems

An intercooled, recuperated engine would have very low specific fuel consumption and emissions. As increases in component efficiencies become more difficult to achieve, changing the thermodynamic cycle to increase the thermal efficiency of the engine could reduce specific fuel consumption by up to 30% over conventional turbofans, with associated emissions reductions.

The intercooled recuperated engine uses an intercooler and recuperator to achieve a change in the cycle. The intercooler is placed within the compressor, where it minimises the power required to compress air by removing the heat from the compressed air while heating the bypass airflow. The recuperator takes heat energy from the core exhaust and transfers it to the high-pressure section in front of the combustor, reducing the amount of heat needed to burn fuel.

Nanotechnology

Nanotechnology enables engineers to coat blades with multiple protecting layers, providing a cost-effective, impenetrable layer which is so thin that neither weight nor dimensions are significantly changed. Gas turbine compressor blades are subject to continual erosion from particulate matter such as water droplets, dust and volcanic ash sucked into the engine. This causes a gradual loss of efficiency, leading to increased fuel consumption, reduced power and higher pollution. Operating costs are increased because of the need to replace the blades.

Coating blades with a protective barrier is cheaper and easier than replacing them, but the coatings must be tough, to withstand corrosion over a long operating periods, and lightweight, to preserve aerodynamic performance.

Rotating detonation engine

Burning fuel with detonative combustion results in a much large pressure rise than can be achieved in a conventional combustion chamber. The rotating detonation engine has a very compact combustion chamber, producing a shorter, simpler engine. The high pressure rise brings improvements in efficiency and therefore fuel consumption, as well as emissions benefits. Research is concentrating on fuel mixture, initiation and propagation of detonation in a cylindrical chamber. Preparations are under way to test a gas turbine engine fitted with continuously rotating detonation combustion chamber.

Continuous injection technology would provide a simpler solution for fuel combustion, as well as higher thrust, in broader operating conditions. Lower NOX emissions are one likely outcome because the engine can operate with either lean or rich fuel mixtures.

Pulse detonation engine

Pulse detonation engines introduce a pulsed detonation in a classical gas turbine cycle. The detonation produces a supersonic combustion shock wave, the resulting very high pressure increase being such that the high-pressure compressor could be reduced in size or even eliminated altogether. Fuel savings of up to 10% could be achieved, depending on turbine efficiency.

Two families of pulse detonation engine have been identified:

- The hybrid version, based on a classical gas turbine in which the combustion chamber is replaced by tubular detonation chambers closed by valves on the upstream side and open on the downstream side facing the turbine
- The combustion wave rotor engine, which has closed detonation tubes and combines detonation with a dynamic pressure increase achieved by compression waves generated in the tubes by the closing and opening of entry and exit doors.

Piston engine injection technology

High-pressure, very fast direct injection systems have potential application in general aviation and military aircraft such as tactical unmanned-aerial vehicles (UAVs). These multimode engines run on different fuels, or gas, and can continuously adjust their mixture to adapt to the load, while compression ratio can be varied by introducing alcohol for high load regimes.

Features include high-velocity piezoelectric servo valves with ultra-short actuation times of a few milliseconds and injection pressures increased by a factor of ten from the current 2,500 bar, drastically reducing NOX and other emissions while retaining the basic engine design. Biofuels are particularly suitable for such engines.

Revolutionary technologies

A number of evolutionary technologies are being studied, covering all propulsion disciplines. Biofuels are amongst the most promising fuels in the shorter term for reducing emissions, with hydrogen a longer term possibility. Electric power in various forms is attracting increasing interest as the necessary technologies mature. For specialised ultra-high-speed air vehicles, ramjets and scramjets are under development.

Sustainable alternative fuels

Non-biofuels

Innovative ideas for non-biofuels are beginning to emerge, such as fuel produced from agricultural waste products, solid waste or from industrial waste gases like fumes produced by the steel industry containing carbon monoxide (e.g. LanzaTech gas-liquid fermentation process that converts CO in alcohol which can be upgraded in hydrocarbon). There is also the «solar to liquid» pathway that could be promising if the process is demonstrated.

Biofuels

Biofuels could bring reductions of up to 15% in greenhouse gas emissions, as well as helping to secure future fuel supplies. Engine lifetime, fuelling infrastructure and fuel consistency considerations mean they would have to replace conventional kerosene with no modifications to the existing system.

Assuming the CO_2 released during combustion is balanced by that extracted from the atmosphere during cultivation through photosynthesis, CO_2 emissions could be virtually eliminated.

The main biofuels under consideration are biologically-obtained hydrocarbons and biohydrogen. A third generation, based on algae, is another possibility.

The most promising state-of-the-art fuels are based on biomass or waste feedstock and Hydroprocessed Renewable Jet, both certified as a 50% blend for use in aviation. These are quite close to compatibility with current engines in terms of energy density, viscosity and temperature. All of the technical details are manageable, and standardisation can be achieved using mineral or bio-additives. There is, however, much to be done in the field of genetic engineering to decode and enhance biomechanisms able to deliver different sorts of biofuels, additives and lubricants.

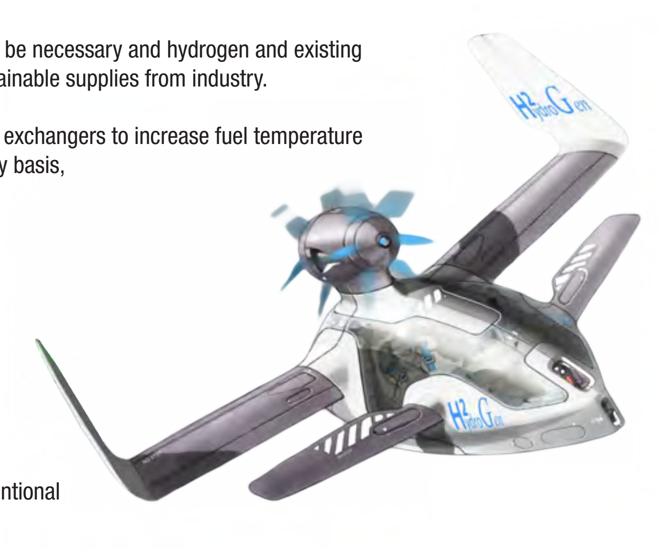
Hydrogen

Hydrogen can be burned in a jet or internal combustion engines, or used to power fuel cells which generate electricity to drive a propeller. The high energy content per mass unit would bring significant payload and range increases, and emissions, particularly CO_2, would be virtually eliminated.

Liquid hydrogen has nearly four times the volume for the same energy output as kerosene and its highly volatile nature precludes storage in the wings. Most designs therefore store hydrogen in the fuselage, leading to a far bigger fuselage volume than for conventional aircraft. The performance of a hydrogen-fuelled aircraft is therefore a trade-off between the larger wetted area (and hence drag) and the lower weight of the fuel, and this depends on the size of the aircraft.

Complete redesign of the aircraft and of the global distribution infrastructure would be necessary and hydrogen and existing infrastructures would have to co-exist. Another challenge would be to develop sustainable supplies from industry.

Liquid hydrogen at -253 degrees C requires heavy insulation of infrastructure, heat exchangers to increase fuel temperature before combusting and a totally new aircraft configuration. On an energy-for-energy basis, liquid hydrogen is considerably more expensive than fossil fuels.



Electrical propulsion

All-electric aircraft

All-electric aircraft use electric motors instead of internal combustion engines. Power comes from fuel cells, ultracapacitors, power beaming, solar cells and/or batteries.

Research is concentrating on development of advanced technologies such as superconducting or liquid hydrogen-cooled cryogenic motors for lightweight, high-performance motors. Electric motors are more efficient and robust than conventional engines and do not lose power at altitude. They are also quiet and emissions-free.

Energy-efficient storage

Highly efficient energy storage devices could bring advances in generation, conversion, distribution and storage. Potential solutions include harvesting energy from vibrations, using thermo-acoustic engines for energy conversion, actively controlling airflows for better energy distribution, and flywheel energy storage.

Energy harvesting devices can be used to capture the energy in unwanted vibrations. They include conventional, miniaturised devices as well as micro devices that use novel methods of energy conversion. Examples include micro heat engines, and micro fuel cells, both of which have power densities comparable to larger-scale power plants, as well as more novel devices such as micro-electro-mechanical systems (MEMS), piezoelectric devices, photovoltaic cells, and biologically-inspired energy conversion devices.

Battery power

One of the solutions to powering aircraft with electric motors is to produce the energy on the ground and store it in onboard batteries. For large aircraft the size and weight of the batteries remains excessive. However, for smaller aircraft electric propulsion appears more accessible and has already been applied successfully in the Yuneec E430 light aircraft. Boeing has proposed combining electric propulsion and gas turbine power on the same aircraft in its SUGAR study, which could solve the issue of the large power density required for take-off.

Fuel cells

Fuel cells are becoming a viable option to power electric motors for small aircraft, and to generate electricity for the more-electric-aircraft architecture increasingly present in commercial aircraft.

Fuel cells are also modular and theoretically any voltage or power can be produced by a series and/or parallel configuration of stacks of cells. Technologies under consideration include the advanced proton exchange membrane (PEM) and solid oxide fuel cells.

The possibility of using a PEM fuel cell stack providing the total power needed by the engine and all the auxiliary systems has been demonstrated in light aircraft, using commercial fuel cell and power management technologies, albeit with reduced speed, climb rate, range and payload-carrying capability. The major challenge is to reduce the size of the electric drive propulsion system (mainly fuel cell, motor and power management system) and to increase efficiency.

Photovoltaic fuel cells

Photovoltaic fuel cells are a promising technology especially for high-altitude long endurance unmanned air vehicle and small aircraft. To be competitive, costs need to be reduced by up to a factor five. At present most of the solar cell market is based on crystalline silicon wafers, but there is now major interest in thin-film solar cells, with film thicknesses in the range of 1–2 μm, that can be deposited on cheap substrates such as glass, plastic or stainless steel.

The development of suitably light, powerful batteries is still several decades away. Solar-powered aircraft powered solely from the heat provided by the sun are being tested, but clearly would not be suitable for 24-hour deployment.

Hybrid electric turbine

Hybrid electric turbines would use the excellent thrust–to-weight ratio of a turbine engine for high-power requirements such as take-off and electrical power for cruise and descent. Cycle analysis has shown that a good compromise could be to install a 4MW electric motor on the low-pressure (LP) shaft. The additional power would be activated during cruise to reduce the power demand on the LP turbine. A simple cycle simulation shows that when 50% of the power required to drive the fan is provided electrically, specific fuel consumption falls by 21%.

The ratio of jet fuel to batteries depends on the mission. Short-range flights would use more battery power, while long-range missions would be mainly kerosene-fuelled. The required electric motor and battery performances are currently unavailable, but could be within the 2050 timeframe.

High-speed propulsion

Research on high-speed aircraft capable of reducing long-range flights to between two and four hours has been ongoing for several years. Speeds of Mach 4 – Mach 8 are necessary, at altitudes from 24km – 30km, which point towards advanced high-speed airbreathing engines such as ramjets and scramjets.

Within the European Union’s Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT) project, theoretical and experimental studies on the design of two high-speed concepts, equipped with dual-mode airbreathing and hydrogen-fed propulsive systems, are being performed in order to demonstrate their feasibility for long-haul flight.

Low NOX combustor ramjet

Combustion of the air-hydrogen mixture required for the pre-cooled (LAPCAT II) ramjet engine results in high levels of NOX production, with a resulting unacceptable effect on the ozone layer. The thruster-combustor design is therefore critical to the future of this concept.

Rich-burn, Quick-mix Lean-burn (RQL) combustion appears to be promising. It involves two-stage combustion in which all of the fuel is injected in the first stage, reacting with a fraction of the airflow and resulting in a fuel-rich mixture. In the second stage the remaining air is mixed with the main flow and reacts with the remaining fuel in a fuel-lean combustion process.

MHD scramjet

A strategy for improving scramjet performance could be based on the Magneto-Hydro-Dynamic (MHD) bypass system. MHD scramjets promise increased combustion efficiency and stability, with more compact design of the scramjet propulsive system. Feasibility has still not been demonstrated, however. Combustor efficiency is critical to overall thruster performance and there remains doubt as to whether the concept is possible without excessive aerodynamic drag.

Nuclear propulsion

Nuclear propulsion was studied in the 1950s, mainly for military applications. The research demonstrated that a 200-tonne aircraft required an 80-tonne reactor, of which 70% of the weight was the shield.

Nuclear waste treatment is a particularly sensitive area for aircraft because of the risk of contamination following an accident, and public perception of the dangers of nuclear power. Research should therefore concentrate on this area first.

On the basis of the likely direction in which nuclear technology will evolve, coupled with environmental concerns and public perception, it seems clear that nuclear propulsion for civil transportation is not promising. However, it should be investigated in order to quantitatively clarify the technical issues. Specific potential applications can be identified as overseas cargo carried aboard unmanned seaplanes or long-endurance pilotless aircraft to replace or compliment surveillance satellites

Alternative configurations

New materials and manufacturing technology are increasing the feasibility of new aircraft configurations, such as the Blended Wing Body aircraft, opening possibilities for major powerplant installation improvements bringing significant reductions in fuel burn and emissions.

Embedded propulsion

Distributed/embedded propulsion places the engines where they can partially or totally ingest the airframe boundary layer, reducing drag and making the downstream flow of air more uniform.

A Blended Wing Body (BWB) configuration distributes thrust generation
along the wingspan by using several embedded, or buried, small engines.
Propulsion can come from two or more engines. Ideally, a higher number, ingesting the entire boundary layer, would be used. Poor fan performance at the boundary layer indicates an optimum of three or four engines and two conventionally-mounted engines.

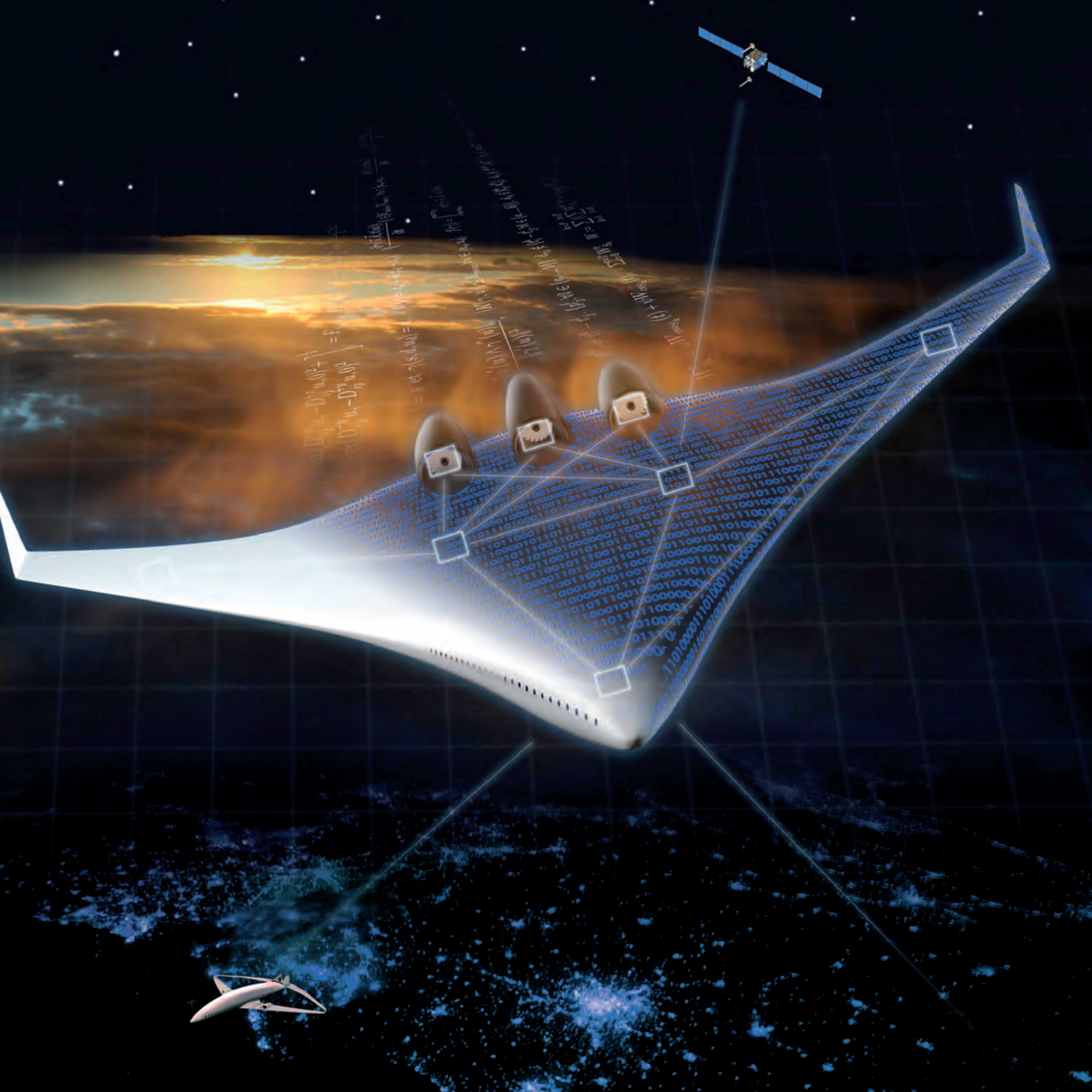
The baseline is a conventional turbofan, but with a gearbox to reduce engine core size and low-pressure turbine size. The core engine is then used to mechanically drive the three fans which, for a 300-passenger aircraft would have a diameter of 1.2m.

The lower weight and noise and higher aerodynamic efficiency of this solution could produce a potential 54% fuel burn reduction, noise levels 46 EPNdB below ICAO Stage 4 and NOX emissions 81% below CAEP 6. Economically, small engines have lower development, production and maintenance costs. Also, because the necessary thrust would be achieved with a number of equally-sized small engines it might be expected that only a few small engine types would need to be developed, which would open the production and maintenance markets to a wider, more competitive market.

Solar energy to improve combustion

The BWB configuration offers an opportunity to cover the upper wing surfaces with photovoltaic elements. A technology breakthrough would be solar cell paint, and some concepts have already been developed and demonstrated. Such a layer, applied to the carbon fibre materials from which the wing would almost certainly be built, would have the additional advantage of improving the electrical properties of the airframe as well as increasing resistance to lightning strikes.

The electrical energy from the solar cell paint would be converted into high voltage/low intensity pulses which would be applied inside the combustion chamber to increase the enthalpy of the gas impinging on the high-pressure turbine, increasing the thermodynamic efficiency of the engine core.



ON BOARD SUBSYSTEMS

Revolutionary on board subsystems

Aircraft subsystems provide functions for the crew, passengers, aircraft and air traffic management system. Because they involve many fields of expertise and technology, a full list of potential solutions for the subsystems of 2050 is likely to be incomplete. Research which can realistically contribute to the 2050 goals will therefore be characterised more by evolution than by revolution.

The term “subsystem” is mainly related to one or several interacting electric, electronic and electro-mechanical on board equipments which support “system” functions or pneumatic/hydraulic equipment related to on board actuation systems.

The study is based on top-down and bottom-up approaches:

- **Bottom-up approach:** This approach surveys existing aircraft systems and analyses them for any possibilities for radical improvements
- **Top-down approach:** This approach analyses the “EREA vision for the future” and the EC’s “Flightpath 2050 vision” documents for potential system implications. It also looks at revolutionary ideas in the other domains to determine the systems technology needed to realise those ideas

Main areas for the development of on board subsystems

All-weather flight at all times
Systems which support the pilot, or in unmanned vehicles, the autonomous flight management system, to fly in all-weather conditions at all times require on board presentation of meteorological data and the technologies necessary for enhanced and synthetic vision to support flight in low-visibility conditions.

Datalinks
A large increase in high-speed data link usage is foreseen, which will require on board subsystems technology. Important aspects are the increasingly stringent requirements on safety (integrity, reliability, availability) and robustness.

Revolutionary energy technologies
Revolutionary new ways of supplying energy to the aircraft will require on board subsystems technology in many areas. Apart from reducing the energy consumption or environmental footprint of individual systems and of the complete aircraft, areas of interest include: efficient, power-dense and recyclable energy storage systems, energy generation and energy control/management.

Advanced health-monitoring and prognostics
Reduction in aircraft life cycle costs, and that of on board systems, can be achieved by improved maintenance, supported by aircraft health-monitoring systems. These enable long-term scheduled maintenance to be replaced by on-condition-based maintenance.

Meta-systems
The ever-increasing complexity of systems and functions brings a need for research into effective and reliable meta-systems which process and interpret the data of many systems at a higher level. A combined flight management system for manned and unmanned aircraft can be foreseen, which shares decisions between the navigation system and the ground operator.

Systems engineering: advances in methods, processes and tools
Development and certification of new aircraft subsystems involves meeting safety and reliability requirements, calling for methods, processes and tools relevant to systems engineering rather than technology development. The development of sophisticated tools supporting the development process will be as important as the development of new technologies.

Large-scale automation
Large-scale automation of the air transport system, as expressed in multiple 2050 visions, will require a massive distributed control system, which will be extremely complex, involving large-scale integration across multiple disciplines.

Standardisation and modularisation
For technology development in general, open systems and standards are important building blocks that allow modularisation. Here, a role is seen especially for research institutes because of their independency. While standardisation is not in itself expected to be useful as a stand-alone research topic, each topic should have standardisation as a goal.

Adaptive, reconfigurable, multi-purpose hardware
One of the challenges will therefore be to enable basic hardware to be reconfigurable, so that it can implement different functions, depending on the flight phase. For non-safety-critical equipment, the weight and volume of dedicated electronic equipment will be replaced by basic, “general-purpose” electronic boards.

Research topics: bottom-up approach

The development of a new aircraft subsystem has to satisfy safety and reliability criteria if it is to achieve certification. Such requirements call for methods, processes and tools relevant to systems engineering rather than to technology development.

The development of sophisticated tools supporting the phases of a development process - design, verification, testing, etc - will be as important as the development of new technologies. The applicability of new technologies will be conditioned by the availability of processes and methods to certify the related equipment. As an example, there is the possible use of artificial intelligence to achieve for full autonomy. Nowadays, functions using artificial intelligence cannot be certified because of their unpredictability. If we do not elaborate new ways to state the reliability, and consequently the safety, of such new paradigms, technologies based on them will no be useable.

Technologies alone are not enough. In parallel, system engineering methods and tools have to be developed in order to apply those technologies in the aeronautical environment.

An overview of research topics defined following the bottom-up approach is proposed below within a non-ordered list.

Reconfigurable communication systems

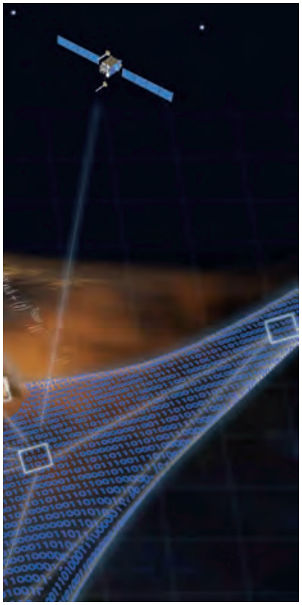
Development of data and voice communication systems based on reconfigurable units. By basing them on a common hardware platform, several advantages could be expected:

- Shorter time-to-market
- Less weight for redundant communications systems.
- Less equipment to load on board.

Disadvantages include certification issues of the reconfiguration function, especially when executed during the flight.

Adaptive communication systems
Communication systems which can adapt some transmission characteristics as a function of the environment include:

- embedded radio channels to best allocate the frequency of operation within a certain frequency band
- adapting transmission data rate to the available power and communication distance
- adapting the modulation scheme to the transmission data rate and signal to noise ratio at the receiver



Greater flexibility and adaptability of communication systems can allow inhabited air vehicles to optimise missions autonomously.

Conformal antennae
Antennae which are conformal to the aircraft fuselage would reduce drag, weight and cost.

Enhanced Vision Systems
Enhanced vision systems can provide safe navigation of both manned and unmanned aircraft. They are especially useful during take-off and landing in low visibility conditions and to prevent runway incursions by clearly identifying runways, taxiways, other aircraft, and people. During approach they improve detection of trees, power lines and other obstacles, improve visibility in brown-out conditions and in haze and rain and help identify rugged and sloping terrain

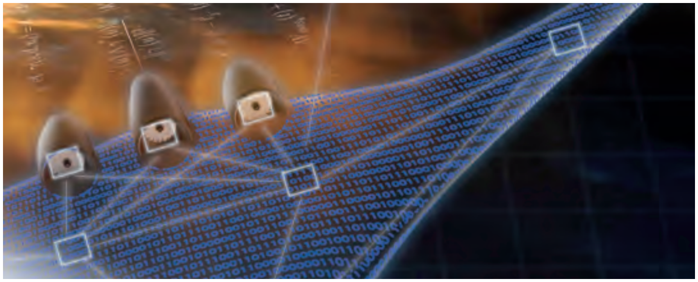
Synthetic Vision Systems
Synthetic vision systems enhance situational awareness and flight safety during critical flight phases. Innovative display systems give the pilot additional information and eliminate distractions arising from using a head-down display.

Combining synthetic and enhanced vision systems would give the pilot full awareness of the external environment regardless of visibility.

Vision-based UAV taxiing and autolanding
UAV autonomy to follow taxiways and detect obstacles could use EVS sensors and an active sensor such as LIDAR, or laser scanner. Reliability of a sensor-based detection system in an automated control loop is an issue. Landing with little or no ground cooperation would greatly increase UAV autonomy.

Fuel cells for auxiliary power unit
Use of high-efficiency fuel cells for auxiliary power units would improve environmental behaviour and be more reliable with respect to internal combustion engines and electric generators. Low energy-to-weight ratio is an issue.

Powerline data communication in aircraft
A powerline data communication network carries data by superimposing a modulated carrier signal on a wiring system. Also used for electric power transmission and to distribute digital data and electrical power to smart sensors/actuators and on board computers. Reduces the weight of data cables, while maintaining the reliability of wired connections.



Wireless in-aircraft data communication
A wireless data transmission channel for communication between aircraft systems and personal electronics devices would reduce the weight of cables and is an enabler for passenger data communication.

Disadvantages include susceptibility to electro-magnetic interference, as well as signal degradation due to materials in the aircraft in the transmission path (e.g. a/c structural parts or other objects). Security is also harder to achieve. Certification may be a challenge as communication of safety-critical data must not be compromised.

Potential research topics: top-down approach

For the top-down approach, higher-level visions of the air transport system in 2050 and concepts developed in the other domains of this study (aircraft configuration, propulsion, automation, airport) have been used to deduce the need for new aircraft subsystems technologies, and therefore the need for subsystems future research.

High level goals Research area	Higher ATS safety	Better ATS capacity / availability	Reduce cost of flying	Reduce impact on environment	Higher flight comfort	Flight security
Systems engineering and advanced design, certification and manufacturing tools	●	●	●	●	●	●
Flight predictability: A computer providing a dynamic model of flight evolution Communication of such data between aircraft and ground-based traffic management to determine an optimum (4D) trajectory	●	●	●	●		
Sensors for on board weather forecasting	●	●				
Advanced health monitoring and prognostics systems	●	●	●			
Subsystems to identify performance degradation of systems (navigation sensors, command system) and flight envelope degradation	●	●	●			
On board system architecture and certification philosophy for a pilot-less aircraft	●		●			
Sense and avoid	●	●				
Sensors to rapidly detect and predict wind conditions	●	●				
Subsystem technology to support close-formation flying for the purpose of drag reduction	●		●	●		
Cockpit display technology, pilot interaction, voice control, synthetic/enhanced vision	●	●	●			
Systems to handle emergency situations at a higher level	●					
Secure and robust high-speed data links for aircraft-to-ground and possibly aircraft-to-aircraft communications	●	●			●	●
Subsystem technology to support all-weather operations. Aspects include: anti-ice and de-ice systems for new aircraft materials (e.g. composites).		●				
Subsystem technology to support active flow control strategies			●	●		
Subsystem technology to support active load control strategies			●	●		
Subsystem technology to support structural morphing for drag reduction			●	●		
Power electronics to compete with existing technologies (bleed air, hydraulic) on topics as specific weight, reliability and cost.			●	●		
Revolutionary energy technologies : storage, generation and combined			●	●		
Energy harvesting			●	●		
Crash-safe nuclear power plant			●	●		
High cruise altitude aircraft requiring new environmental cabin and oxygen system.		●			●	
Subsystem technology to support active reduction of (outside) noise		●		●	●	


HydroGen

TOWARDS FULL AUTOMATION?

The road to full automation

The ever more complex air transport system facing more and more ambitious goals is naturally evolving towards automation. Whatever the degree of automation, the ATM system will continue to comply with its key performance areas: service level, environment, safety and security, increased capacity, airline cost, flexibility and predictability. The aim here is to define the biggest challenges in the path towards a high level of automation, full automation representing the ultimate evolution.
A highly automated air transport system is based on three pillars: the 4-dimension (4D) contract, automated air traffic management and automated aircraft.

Four-dimensional ATM contract

The 4D ATM contract is the central operational concept enabling the global optimisation of air traffic management. It provides the framework for automatic handling of the flight management of all air traffic participants by a central ATM system ensuring safe separation and optimisation of all flights, according to global performance criteria.

A 4D contract can be represented as a time dimension moving along with a three-dimensional airspace tube assigned to each aircraft by the ATM system and/or negotiated by the aircraft themselves. All aircraft must stay within their assigned 4D volumes (i.e. respect their contracts) for the entire duration of the flight. As long as they do so, they are guaranteed conflict-free trajectories and the entire air traffic system is globally optimised to the extent of the capability of the central system.

All 4D contracts are generated by the central ATM system (strategic planning). Each contract is issued for the entire flight, including ground operations, and is conflict-free in relation to all other contracts. The aircraft are in charge of executing their contracts and the ground system monitors them. Under certain circumstances, such as emergencies or off-nominal situations, the contract can be updated on-board the aircraft (dynamic planning).

The implementation of a 4D contract-based ATM system will bring significant improvements to ground and on-board systems, both on technology and conceptual levels.

Automated air traffic management

Ensuring that the air traffic system has total situational awareness under all weather conditions, including low visibility, requires a range of sensors to detect aircraft movements, movements of other vehicles, and a view of all other relevant objects, like birds and debris on the runway. As a result, control towers at the airport will no longer be necessary and will be replaced by remote towers.

An automated conflict detection system acts immediately once a conflict is detected. The action will not involve the «controller» – as called today – but will be notified to the aircraft or vehicles involved, which will automatically take appropriate action.

The transition towards automated ATM has been ongoing for several years. Airspace sectors are bigger, direct routing is replacing strict airways and controllers are supported by 4D-planning tools in order to increase efficiency, predictability and throughput.

This transition will continue, ultimately resulting in a shift from a human decision maker supported by assistance systems towards advanced automated decision systems managed by a human. On the way, challenges are found on the human-machine interface (HMI) level and legal issues.

Automated Aircraft

By 2050, the «pilot» (as called today) will monitor the aircraft instead of taking active actions.

The aircraft is at the heart of the fully-automated ATM system and will have to accomplish all required tasks safely.

The key aspect of aircraft automation is a complete implementation of the 4D contracts concept. However, the transition phase where there will be a mixed traffic of automated and non-automated aircraft needs to be thoroughly investigated.

Aircraft will be responsible for monitoring their commitment with their 4D contract «signed» with the ground ATM centre. In cases in which it is impossible to fulfil the contract or in an emergency, the aircraft will be able to dynamically update its planning and will inform the ground ATM centre of its actions.

Thus, aircraft will have to collect and manage information on other air traffic, weather, communications, navigation and surveillance infrastructure status, airports, terrain and obstacles and continuously check subsystem status to perform real-time evaluations of their capacities and performance limitations.

By 2050, airborne automation should be advanced enough for:

- Adaptive 4D trajectory management and on-board re-planning capability for negotiating trajectories with the ground system
- A complete, or extended, sensor fusion system, deriving navigation/control data from all on-board sensor systems
- Comprehensive health monitoring of system integrity

Pilots will be assigned with a role quite different from the current one. They will be kept in the loop, but (similarly to the air traffic controller in the foreseen automated ATM system), will monitor the operation instead of taking active actions and command over the aircraft. Thus, we will not talk about pilots and controllers anymore but about managers and supervisors.

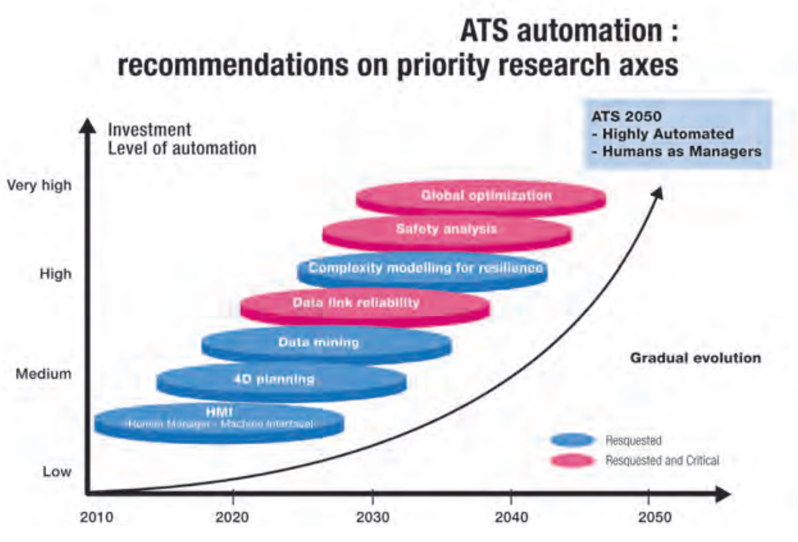
Challenges

Enabling technologies paving the way towards full automation are already being studied, but many are still at low operational levels. Naturally, the shift towards full automation will not happen overnight, but will rather be an evolution in which more and more tasks are executed by automated systems.

The figure below shows a schematic overview of possible technological evolution towards a high level of automation.

Developing realistic models

Creating sufficiently realistic models for research is a major challenge as systems become more complex and interactive. The biggest challenge lies in testing the interaction between elements of the system. New modelling techniques and methods to validate models will be necessary to build the ATM system of the future. Standardized models that allow coherent and comparable testing at different sites would be a major step in ATM simulation. As different models could be compared more easily, the development cycle of new techniques could benefit as decisions about the most promising techniques become much easier.



Human-machine interface

The main challenge in designing a next generation human-machine interface (HMI) for ATM is deciding which information not to present. As the potential amount of information will be huge, only information that is necessary for next-generation controllers to execute their tasks should be presented. Advanced monitoring tools will be necessary to verify if the planning is properly executed. In case a problem arises that cannot be solved by the automated tools, the ATM manager will need to be brought in the loop by presenting the right information such that he can make a deliberate decision.

Interoperability and data collection

The path towards full automation puts high demands on the timely availability of the right data in the right place at the right time. As the current ATM system consists of a huge number of incompatible systems, interoperability is a major challenge. Systems will need to be interconnected and data should be shared and made available among stakeholders using standardized protocols and formats.

Data mining

As more and more systems become interconnected, it is important to be able to locate and extract the right information. New data-mining algorithms are needed to support data extraction and selection.

Sensor fusion

Current onboard and offboard sensors provide a wealth of information. Often this information is (partially) overlapping. Sensor fusion aims to combine the various sensor information sources to provide a single, optimised, view of the world. For the future, innovative sensor fusion algorithms need to be developed which are extremely tolerant of any system failure. Situational awareness must be guaranteed in all weathers conditions, all times.

Innovative sources of data will be created which offer accurate weather forecasting before and during the flight. New SAR technologies, molecular/optical air data sensors and multiple magnetometers for advanced attitude determination will have to be developed. Such technologies will enable fully automated operations with low cost, weight and size. However, more onboard computational power will be required for real-time implementation.

4D contract: ground

Automated global strategic planning will lay the foundations for a global approach to air traffic management which provides safe separation of aircraft as well as maximizing capacity, while minimising costs, delays and environmental impact.

Strategic planning aims to find global solutions for all contracts assigned to aircraft in a large airspace (such as Europe or USA). It takes into account all significant factors and generates a set of contracts which offer the best trade-offs between all the main key performance areas.

To represent the interests of all aviation stakeholders, the system will use the principle of collaborative decision making. However, as the system will be oriented towards a globally optimal solution, each stakeholder will take part in the collective decision process by inputting his own criterion. The system will use an efficient multidisciplinary and adaptive optimisation method, including all relevant criteria in the planning of contracts and adapting to the dynamic nature of the ATM where changes in the number and domain of the solution variables are frequent. Currently the traffic management and flight management tasks are distinct concepts which correspond to different phases of ground planning activity. It is likely that at some point the two will be unified. Flight management activity will be integrated with the same automated global optimisation process which initially would solve the air traffic management problem.

Eventually the ground planning centres will take charge of calculating and assigning new optimised contracts even after take-off as factors change on-board and in the air (such as weather, airport closures, emergencies etc.), ensuring the global ATM solution remains optimised and safe for the duration of each flight.

4D contract management: airborne

Unexpected changes in meteorological conditions or degradation in either aircraft or systems performance, could prevent an aircraft from maintaining its 4D contract.

In such cases, as normally envisaged, a “tactical” re-planning process would be used and a new contract agreed between the ground and airborne segments.

The distinction between a contract and a trajectory should be explained. A contract represents the space-time reserved portion assigned to an aircraft to complete its flight, while the trajectory is the actual path the aircraft will fly (while remaining within the contractually-defined airspace).

The contract will be defined, through a strategic or tactical planning phase, on the ground or, in certain emergency conditions, on board the aircraft that will immediately inform the ATM system. Trajectory monitoring and control within the assigned contract tube is the responsibility of the aircraft.

Automated airport operations

Passenger travel

In a fully automated airport, passenger interaction with airport staff for check in, baggage drop-off, security, border control, and boarding, will disappear, or at least be minimally experienced.

Some processes, like the formal check in procedure, will disappear completely. Many passengers already travel with electronic boarding passes which are uploaded to their smartphones and do not need to physically check in. Research on less visible and less intrusive security processes is ongoing.

Aircraft handling

The airport will be able to maintain a sustainable capacity under all weather conditions. This means aircraft handling processes need to be more efficient, with reduced runway occupancy and gate handling times.

Aircraft will be fully integrated with the air transport system, their 4D flights planned throughout the business trajectory. Aircraft handlers will be fully informed about the status of each aircraft. Delays will be reduced to a minimum, so that the predictability of operations increases, improving the efficient planning of resources.

Where infrastructure allows, aircraft handling can be performed in the intelligent infrastructure. Automated boarding bridges, electrical power supply (if still necessary), and fuelling from pumps located directly below the aircraft will reduce dependence on human resources. Personnel still required will be equipped with hand held devices providing all necessary information about the status of the aircraft.

Connection between aircraft and passenger

Passenger boarding and de boarding will need to be more efficient, with fully automated processes during which they are kept informed on the status of their flight (and vice versa the aircraft handler should know the status of each passenger). Special attention to the location of individual passengers will be necessary for those who are transferring to another flight.

Full automation will require fully operational individual passenger planning systems that will enable the aircraft to be informed of the status of each passenger taking the flight.

Intermodal transport

Global optimisation can only be achieved by broadening the concept towards intermodal transport to the entire transport system.

The aim is to increase the efficiency of the overall transport chain by improving the interoperability of different modes of transport, increasing environmental sustainability and making more efficient use of the existing infrastructure.

Interconnection of the air transport system with land and sea surface transports is mandatory. This interconnection will be carried out at physical and management levels. The physical level involves airports and other transport systems, while management, through a centralised integrated transport management system, will provide communications and interconnection among the different stakeholders at strategic, tactical, and operational levels.

Health monitoring

To achieve a high level of autonomy and support the wide delegation of responsibilities to on-board systems, the development of advanced health monitoring systems is required.

Maintaining the performance-based navigation system at the heart of the 4D-contract concept will require special attention to the development of algorithms which can identify performance degradation of systems such as the navigation sensors and the command system.

A further aspect is the development of systems for vehicle and system diagnostics to watch for trends which indicate a potential forthcoming failure.

Emergency handling

Today, flight procedures are subdivided into normal, abnormal, and emergency situations.

In a highly automated environment, systems should contain built-in rules to handle abnormal and emergency situations. Statistics indicate for more than half of all aircraft accidents as reason human error, so it is reasonable to ask whether the system itself or the responsible human-in-the-loop manager should respond to abnormal situations.

Aviation systems are usually designed as human-assistance systems which provide advisories to the operator. In the future, fully automated systems will decide and execute actions, and the operator will have a managing and supervising task. If an error occurs, the human will be able to intervene to solve problems the system is not able to solve.

Full automation will enable more systems to be operated with fewer humans (i.e single pilot cockpit, single European sky), although this will reduce the situational awareness of an operator for a particular emergency. If humans are supposed to handle these situations, it is essential to identify how the operator should focus on it in an efficient and safe way.

On-board planning and optimisation

Flight planning capabilities at the tactical level could be carried out on-board to address or support some relevant functionality, such as separation management, or a particular flight condition, such as flying with degraded performance.

As far as separation management is concerned, there will be further delegation of separation responsibility to provide tactical conflict resolution avoidance of weather, airspace, terrain and other hazards. Specific algorithms will resolve conflicts at least several minutes ahead of predicted conflicts. The resolution manoeuvre is usually very small and generally includes course, speed, or altitude changes.

In general, a 4D contract assigned to a self-separating aircraft will be sufficient for the aircraft mission. After an unplanned manoeuvre, the aircraft would be expected to return to its original route (or contract). In cases where it is required to move a significant distance from the original contract a new 4D-contract could be negotiated.

The development of algorithms for on-board trajectory planning, auto piloting and flight controls is also relevant to continuously adapt the trajectory to manoeuvres occurring as a result of malfunctions.

Modelling and safety analysis of the future ATM system

The introduction of new procedures and technology in a complex system such as a fully automated ATM system needs to be appropriately evaluated, both from performance improvements and, above all, from a safety risk assessment point of view.

The ATM system is a “system of systems”, that is a series of individual interacting entities, each one a combination of continuous dynamics (e.g. aircraft dynamics) and discrete transitions (e.g. pilot decisions / autopilot modes / ATC actions). Methodologies and technologies will therefore have to address the development of efficient tools supporting a modelling approach for the proposed complex future ATM system, along with performance and safety verification in realistic traffic scenarios.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AIRPORT

Airport 2050: a revolution in capacity and efficiency

The airport of 2050 must be driven by the dual requirements for increased capacity and improved efficiency. Airport location, layout and equipment will take into account environmental concerns as well as passenger comfort. Airports must also function with the highest possible levels of safety.

Four main drivers for the airport of 2050 have been defined:

Environmental

Dramatic reductions of emissions (CO2, NOX) and perceived external noise will be essential.

Capacity

Airports are a critical component of the air traffic system and there are reliable predictions that they will have to cope with higher numbers of traffic and passengers.

User comfort

The main goal for 2050 is fast, reliable and comfortable door-to-door travel, independent of the mode of transport. This passenger-oriented air transport system will be focussed on time-saving through reduced delays and queues, along with comfortable and user-friendly procedures. Optimal, reliable connections between different transport modes will lead to significant reductions in travel times

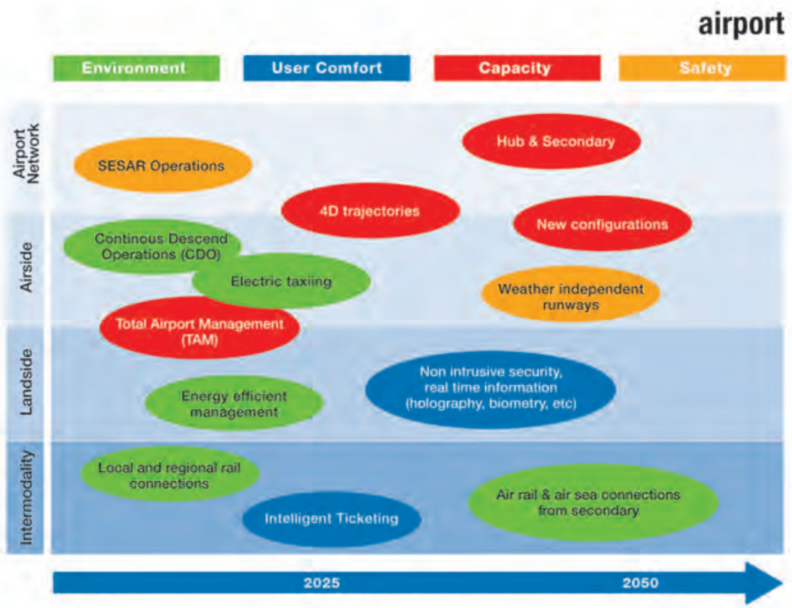
Safety

The expected increase in air transport is very closely related to the trust passengers have in the system. Only with the highest level of safety regarding systems, operators and procedures can the 2050 goals be achieved.

General concept for the 2050 airport

The following are seen as critical elements:

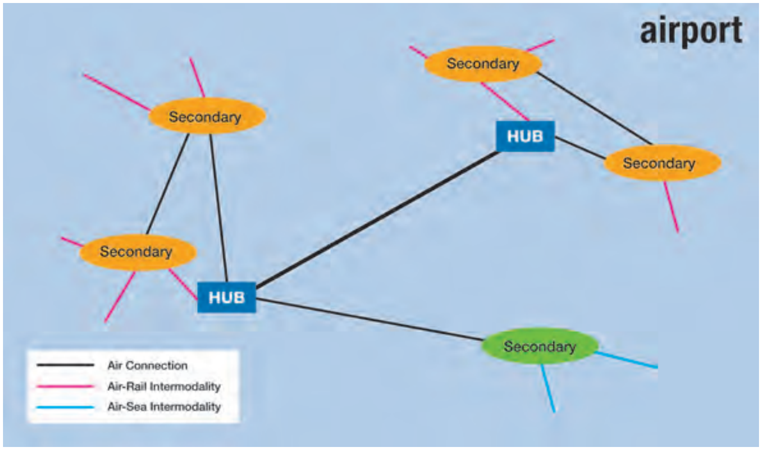
- Air traffic management will be related to a network of airports rather than local and individual airports
- Landside and airside components need to be re-thought and intermodal means of transport described



Evolutions of the airport.
The different concepts are related to one or several drivers: environment, user comfort, capacity and safety

The airport network

The airports of 2050 will be integrated into a network of air, ground and even water transport that will enhance capacity and make transportation more efficient. The airport network will be mainly composed of hubs connected to secondary airports that will provide services to a greater number of users and operators.



Overall concept of hubs & secondary airport connections

Connections between hubs and secondary airports will be possible by means of efficient and environmentally friendly public transport, but will also include an optimised network for private transportation that will enable the efficient, safe use of personal ground transport. Ships may be used to connect secondary airports, depending on their location.

Air transport will include current-configuration aircraft, plus other actors such as personal air transportation vehicles or aircraft with passengers pre-loaded into standard fuselage boxes. In addition, different types of runways as well as take-off and landing assistance systems will be available to provide services for conventional take-off and landing aircraft, short-take off and landing air vehicles or convertible vehicles. Airport networks should be designed to accommodate them all.

Interconnections within this network will be provided by multimodal transport, including high-speed trains for the national or international network, trains, subways, tramways or suburban trains at regional airports, electric ground vehicles, environmentally friendly ships or even air-buses.

A passenger-oriented airport

The 2050 airport will use new technologies to make passengers' stay in the airport as short and comfortable as possible. One of the most important challenges will be achieving public confidence in automation, although this will demand significant advances in technology.

Automation will mean that users are informed about the current status of their journey and alternative options, periodically or on demand. Information points will be distributed around the terminals and interactive devices embedded in transport systems so that passengers can access travel information at any time using smart phones or interactive panels/screens situated along the intermodal transport network.

Operations

By 2050, the Single European Sky (SES) four-dimensional (4D) air traffic management system will have been fully implemented. It will be important to provide airport networks with the capability to coordinate/ manage ground operations with 4D airborne operations.

Within this timeframe, several scenarios could be envisaged:

- Commercial aircraft to or from hubs. Passengers would access airports using the intermodal transport system
- Personal transport systems to or from secondary dedicated airports connected with the home by air-rail transportation
- Hub and secondary airports connected, enabling passengers using personal aircraft to reach the hub and transfer to commercial aircraft.

Information Handling and Collaborative Decision Making

An integral element of the airport of the future is the handling of information and the collaboration of all involved stakeholders. Total Airport Management (TAM) will be expanded, the role of operators changing from tactical to pre-tactical and from specialized controlling functions to multi-system management. Coordination of the overall network system at airports and between airports will be necessary. Decision-making will be supported by high-performance automated systems operating on an enormous amount of data providing statistical analyses, overview of the actual situation and prediction of the future. With the automation of more and more processes, the amount of data that needs to be handled will increase significantly. New structures and concepts of data handling will therefore need to be developed.

Airside operations

In the short term, the airside will take advantage of improvements resulting from the SES programme and will evolve towards higher automation. The airport infrastructure will include revolutionary architecture adapted to any new aircraft configuration and propulsion mode (i.e blended wing body and new fuels, such as hydrogen or biofuels).

New airport layouts and runway configurations could overcome weather restrictions and maintain capacity. A revolutionary airside development could be a circular runway, adapted to any wind direction, to increase capacity. Associated to a terminal centered in the 'circle', such runways would enable short, fuel-saving taxiing along radii adapted for capacity and safety.

Runways

Capacity

Real or actual capacity is usually lower than declared capacity because of weather restrictions and dependencies between runways. Current trends in airport runway operations will optimise the use of the existing runway system through:

- Improved planning resulting from SESAR trajectory-based operations
- Increased use of noise abatement operations
- Capacity increases from better understanding of wake-vortices, enabling reduced separation and new approach procedures

Location and size of runways

Revolutionary concepts to save space and/or to enable operations to alleviate pressure on inhabitants include:

- Remote runways, possibly in the sea
- Large runway surfaces, enabling operations from any direction
- Large circular runways enabling operations from any direction
- Double-deck runways
- Airports in the sky (cruiser – feeder concept)

Operational procedures

Revolutionary concepts to enable more efficient runway usage include:

- Formation flying or paired arrivals on one or several runways
- More entrance and exit points to one runway
- High-precision approach systems to allow reduced separation through flying different approach paths towards one runway

Landing and take-off power
Revolutionary concepts for reducing engine power during take-off and landing include:
- Catapulted take-off
- Rail system and ground-based electric power to accelerate the aircraft
- Rail system or land-based cart system to land
- Tractor beam for landing
- Arrester cables to help braking

All-weather operations
Revolutionary concepts for the increase of capacity independent of weather conditions include:
- Onboard equipment allowing landing with significant tail or crosswinds
- Onboard equipment to display weather information and airport infrastructure in low visibility conditions
- Fans or other equipment to blow fog and wake turbulence away
- Ground-based runway heating

Taxiways and Aprons

Electric taxiing

Electric taxiing can be achieved with an electrically-powered nose wheel, or electric vehicles called taxibots connected with the aircraft nose wheel and operated from the cockpit. Aircraft engines can be shut down, leading to reduced fuel consumptions and emissions. Such vehicles could be driven autonomously and fully automated.

Electric Energy

To reduce emissions, fossil fuels can be replaced by electrical power generated by more environmentally-friendly methods. A major challenge is the provision of the large amounts of energy needed to operate all of the vehicles and to guarantee its availability at all times and under all weather conditions.

Power generation using solar or geothermal systems needs to be integrated into the future airport infrastructure.
Terminals could have large solar panels on the roof or on airfield areas not used for aircraft or ground vehicles.
Wind farms could generate the necessary energy for offshore airports.

4D Trajectory Operations on the ground

Ground-handling management systems will be able to optimise the allocation of ground-handling vehicles. With fully available high-speed datalink communications, relevant information between all actors at the airport is shared instantly. All areas are equipped with wireless access points to ensure data availability. New datalink concepts will have to integrate different technologies using conventional ground and satellite-based communication systems. There is already a vision for this in the SESAR programme.

Landside operations

The airport landside is the interface between air transport service providers (airlines, airports etc.) and the passengers. Therefore, future landside infrastructure and services must focus on passenger's needs and comfort.

Future airport terminals will be much less time consuming for the passenger. One example is at check-in, which does not have to take place inside the airport, but can be performed at home, at the hotel or using a smart phone.

Airport terminals will have short walking distances for passengers. Moving walkways and individual automated guided vehicle systems will cover long distances conveniently and quickly between different terminals and within large terminals.

Passengers will have information available at all times, providing a comprehensive choice of the modes of transport, prior to travel as well as in the case of rescheduling or unforeseen disruptions.

Intermodality

A major goal for the future intermodal transport system is to reduce dependence on the automobile as the major mode of ground transportation and increase use of public transport, especially in the case of the future air transport system.

Underground railway stations built below terminals reduce the need for private cars as well as limiting the environmental footprint. Intermodality can be envisaged at several levels, from local public transport to international connections:

- City centres and suburban areas have to be accessible using the tramway or subway connecting with railway stations located on the airport landside
- At regional level, connections to a high-speed train is a strong advantage for an airport's attractiveness if it is rapid and serves the nearby cities
- For national / international connections
  - Integration of airports within a regional/national railway network or other future modes of public transport
  - National railway stations at airports must be part of the landside, where the passenger journey starts with passenger check-in and luggage deposit
  - High-speed train connections to connect regional megacities
  - Connections between regional airports to major hubs with high-speed train as an alternative to short-haul air services, releasing slots and relieving airport congestion

The airport landside should provide inter-terminal shuttles to provide convenient, fast and reliable services for the passenger and luggage. Automatic subway trains and/or tramways should be considered instead of buses.

Door-to-door journey

In the door-to-door approach, the airport landside is enlarged or redefined:

- Railway stations are part of an extended 'landside'
- The journey starts anywhere in the public zone
- Security checks and luggage registration/deposit are done in the railway station, on board a train or in dedicated points in a city
- Quick & easy checking using, for example, biometry
- Luggage transportation from home to the terminal/plane (or door to door) is available
- The subway or railroad serves all the terminals/gates: long walks are no longer needed to reach any point in the airport (especially with underground terminals)

Airside-landside connection

Different systems within the airport have their own information management systems, which must be collected and managed with a holistic, centralized approach aimed at achieving a seamless flow of passengers and luggage.

Passenger

Each category of passenger has their own requirements in terms of services, timing and dedicated spaces within the airport and possibly on the apron/ aircraft.

An advanced system devoted to safety, security, dynamic risk management and passengers' satisfaction could contain:

- Baggage tracking and reconciliation for each item of baggage
- Extension of baggage identification techniques
- Application of multi-scanning devices based on innovative screening techniques for detecting dangerous materials
- Automatic aircraft load balancing procedures

The following technologies will be important:

- Localization
- Voice and datalink communications
- Communications for handlers and drivers
- Technology for detecting, locating, tracking and tracing passengers, integrated with ticket information

Boarding

Landside security checks can be performed biometrically while the passenger is in the airport. This will require:

- Optimising the position of the security checks
- Optimising gate planning
- Allowing passengers to choose the way they reach the aircraft, depending on the availability of time

Aircraft

Automated tracking of equipment and maintenance activities will be based on innovative techniques for fusing information from data processing systems and monitoring devices (high-resolution radar, cameras, radio-communications, GPS/EGNOS).

Use of identification systems for monitoring and interpreting the activities of apron vehicles and operations will allow automatic detection, tracking and classification through distributed sensors and a management data system.

Technologies for the airport of 2050

The table below summarises the technologies and competences offered by the aeronautical research centres that will make major contributions to the airport of 2050.

Airport component and functions		Promising technologies	drivers
Airport Network	Passenger-oriented airport	Two-way communication devices: - Datalink technologies and wireless communications - Cloud computing, computer identification, human-machine interfaces - Robotics: assistance robots. Terminal transport systems	User comfort Capacity
	Operations	Data fusion techniques, field sensor network Vision techniques, remote sensors and acquisition devices for security check Information & Communication technology, dynamic multi-risk management New aircraft configurations New aircraft procedures and new procedures management	Safety Security Environment Capacity
	Information handling and collaborative decision making	Optimisation analysis based on multi-actor, multi-objective, risk monitoring, management system, sensors and ambient intelligence Near-field communication technologies, RFID, Bluetooth and mobile devices, LED bar codes Development of multi-scanning devices Voice and data link between base-station and vehicles, various transmission technologies GPS, Galileo, high resolution radar	Capacity Safety Security
Airside	Ground-based noise measurements	Develop noise-preferential approaches Noise monitoring and modelling Noise walls or anti-noise interferences systems	Environment
	All weather operations	The aircraft as a meteorological sensor Improved instant forecasting (i.e for strong winds) Information sharing with other air vehicles and the ground	Capacity Safety

Airport component and functions		Promising technologies	drivers
	Air quality improvement	New technologies to reduce fuel consumption (TO, taxiing, APU…) Develop air quality monitoring: numerical forecast at local scale and measurements	Environment
Airside Runways	Capacity	Improvements of operations planning (SESAR and post-SESAR)	Capacity
	Location and size of runways	New runway concepts: double-deck runways to reduce land use, Airports in the sky	Capacity
	Operational procedures	High precision approach systems to reduce separation	Capacity Safety
	Reduced separations	Wake vortex monitoring and modelling	Capacity Safety
	Landing and take-off power	Develop new concepts: catapult, rail system, tractor beam, cables …	Environment: noise and emissions reductions
	4-D Trajectory Operations on the ground	Data network able to support 4D operations (ground and air) Datalink and data transmission	Capacity Safety
	Electric taxiing	Develop electric nose wheel powered by a fuel cell or electric energy Use of special electric powered vehicles (Taxibot, autonomous or controlled by the aircraft)	Environment
	Electric Energy	Develop energy sources from solar (roofs of terminals), geothermal, wind parks (especially in offshore airports)	Environment
Connection Airside Landside	User-oriented terminal concept	Geo-localization and wireless technologies Datalink	User comfort Capacity
	Baggage handling	Baggage identification techniques: radio frequencies (RFID), chip Security screening techniques (fast, secure, reliable) Automatic aircraft loading calculations	User comfort Capacity Security

Airport component and functions		Promising technologies	drivers
	Boarding mechanism	Multi-biometrical techniques	User comfort Capacity
	Aircraft process	Data fusion from heterogeneous sources Multi-camera visual surveillance systems for ground movements monitoring	Security Capacity
	Cargo	New configurations (Blended Wing Body aircraft) Goods tracking: RFID Capable security screening technologies	Security Capacity
Landside	Energy efficient facility management	Develop passive buildings for terminals, renewable energy Buildings adapted to real weather conditions?	Environment
	Decrease passenger time consuming	Automation of terminal processes Wireless technologies Data fusion covering whole travel chain Data link technologies	User comfort
	Non-intrusive Security	Remote sensing imaging (scanner) Security screening techniques of persons and (hand-)baggage (fast, secure, reliable)	Security User comfort
Intermodal	Door to Door travel	Data bases management Biometric controls	Security User comfort
	Intelligent & Interactive ticket	Wireless technologies, GPS etc. Network of sensor & Data fusion Data link technologies	Environment Security User comfort

ACRONYMS

ACARE	advisory council for aeronautical research in Europe
ATAG	air transport action group
ATC	air traffic control
ATM	air traffic management
ATS	air transport system/air traffic services
APU	auxiliary power unit
BWB	blended wing body
CAEP	committee on aviation environmental protection
CFD	computational fluid dynamics
CFRP	carbon fibre reinforced plastic
CO2	carbon dioxide
DNS	direct numerical simulation
EC	European commission
ECAM	electronic centralised aircraft monitor
EGNOS	European geostationary navigation overlay service
EPNdB	effective perceived noise level in decibels
EREA	association of European research establishments in aeronautics
EM	electromagnetic
EVS	enhanced vision system
FMS	flight management system

GPS	global positioning system
GNSS	global navigation satellite system
GLONASS	Russian GNSS
HALE	high altitude long endurance
HMI	human machine interface
HUD	head-up display
ICAO	international civil aviation organisation
ICT	information and communications technology
LED	light emitting diode
RFID	radio frequency identification
LIDAR	light detection and ranging
MEMS	micro electromechanical systems
NOX	nitrogen oxides
PEM	proton exchange membrane
SAR	synthetic aperture radar
SESAR	single European sky ATM research
SUGAR	subsonic ultra-green aircraft research
UAV	unmanned aerial vehicle
WiMAX	worldwide interoperability for microwave access
WLAN	wireless local area network

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