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The potential of future aircraft technology for noise and pollutant emissions reduction

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ABSTRACT

The negative external impacts of aviation are currently under unprecedented scrutiny. In response, a number of studies into future prospects for improvement have recently been carried out. This paper reviews these studies and discusses their combined implications for emissions of carbon dioxide, oxides of nitrogen, and noise. The results are also compared with targets for emissions reduction proposed by ACARE and NASA. It is concluded that significant future gains are achievable, but not to the extent implied by the ACARE and NASA targets, which represent an unrealistically optimistic view of technological potential over the next 20–40 years. The focus on technological advance also deflects attention from the substantial benefits available from combining present-day technology with behavioural change. Finally, difficult policy decisions will be necessary; the greatest benefits are associated with technological developments that will require major, and long-term, investment for their realisation, and there will be increasing conflict between environmental and noise goals.

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1. Introduction

The introduction of jet-propelled passenger transport aircraft 55 years ago ushered in an era of unprecedented human mobility. Equally, it was associated with noise and local air quality issues that were painfully obvious to those living near airports. Today, these aircraft emissions are regulated, with benefits that are immediately evident to the naked eye and ear when vehicles from the two eras are compared directly. Unfortunately, however, much of this improvement is offset by the huge increase in air traffic over the intervening period. As a result, pressure to reduce noise and local chemical pollutants (specifically oxides of nitrogen, or ‘NO*x*’) remains high.

In addition, early jet engines were extremely inefficient; they displaced propellors nonetheless because of their ability to deliver thrust at high flight speed with low weight. Historically, their efficiency was not seen as an environmental problem, and the only driver for improvements was fuel cost. Now, however, with carbon dioxide (CO_2) from the combustion of fossil fuel recognised as the dominant source of climate change, there is also societal pressure. As a result, the negative external impacts of mass air travel are under scrutiny as never before.

In 2001, recognising this situation, the Advisory Council for Aviation Research and Innovation in Europe (ACARE) published a ‘vision’ for 2020 (European Commission, 2001); this set targets of 50% reductions in fuel-burn and perceived noise, and 80% in landing/take-off NO*x* emissions, relative to year-2000 aircraft. With both Airbus’ and Boeing’s plans to this date now established, it has become clear that these targets will not be achieved. They have been replaced by a new set, ‘FlightPath 2050’ (European Commission, 2011), which calls for reductions of 75%, 65% and 90% respectively by 2050. In the U.S., similar goals have been proposed by NASA for the ‘N+2’ (service-entry 2025) and ‘N+3’ (service-entry 2030–2035) generations of aircraft (Collier, 2012). These are summarised, along with their ACARE counterparts, in Table 1. (Note that CAEP 6 and Stage 4 are regulatory levels; they are explained in Section 2.) Associated with this activity has been a surge in studies into future mitigation prospects, many of which

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Abbreviations: ACARE, Advisory Council for Aviation Research and Innovation in Europe; BPR, by-pass ratio of a turbofan engine; BWB, blended wing-body aircraft configuration; CAEP, Committee on Aviation Environmental Protection; CO_2, carbon dioxide; CRC, Conceptual Research Corporation (NASA N+3 contractor); EIS, entry into service; EPNdB, effective perceived noise level in decibels; GBD, Greener by Design (Royal Aeronautical Society); HLFC, hybrid laminar flow control; ICAO, International Civil Aviation Organisation; ICR, inter-cooled recuperative engine thermodynamic cycle; LFW, laminar flying wing aircraft configuration; MIT, Massachusetts Institute of Technology (NASA N+3 contractor); NACRE, New Aircraft Concepts Research (EU project); NASA, National Aeronautics and Space Administration; NLF, natural laminar flow; NO*x*, oxides of nitrogen; SAI, Silent Aircraft Initiative (Cambridge-MIT Institute project); TW, conventional, ‘tube and wing’, aircraft configuration

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Table 1
Fuel-burn and emissions reduction goals put forward by ACARE and NASA.

Category	ACARE		NASA	
	Vision 2020	**FlightPath 2050**	**N+2 (2025)**	**N+3 (2030–2035)**
	Relative to year-2000 aircraft		*Relative to year-2005 best-in-class*	
Fuel	50%	75%	50%	60%
	Relative to year-2000 aircraft		*Relative to CAEP 6*	
NO*x*	80%	90%	75%	80%
	Relative to year-2000 aircraft		*Cumulative, relative to Stage 4*	
Noise	50%	65%	42 EPNdB	71 EPNdB

invoke either radical technology developments or novel aircraft configurations.

The time is thus ripe to take stock, and this is the aim of the current paper. In particular, we seek to review the potential of technological advances in the aircraft itself, in the light of ACARE's and NASA's stated goals. At this point, it should be recognised that some contribution towards the fuel-burn and noise targets is envisaged from operational improvements, via elimination of air-traffic-management inefficiencies and alterations to landing approach procedures (see Reynolds, this ssue). Aspects of the latter that are relevant to the regulatory noise measures targeted by ACARE and NASA are accounted for in the studies reported here. Efficiency gains in air-traffic management are typically not; however they have progressively less impact as the fuel-burn target becomes more aggressive. (For example, if 5% of current fuel consumption is due to air-traffic-management inefficiencies, and 60% reduction is required, the aircraft-alone reduction must be 58%.) We will therefore compare predicted technological benefits directly with the targets.

As a final point, one could question the use of fuel consumption as a metric. Emissions of the associated pollutant, CO_2, can also be reduced via the use of alternative fuels (see Hileman and Stratton, this issue). This issue, however, is outside the scope of the current review.

The structure of the paper is as follows. We first consider the relevant pollutants, and the factors influencing their generation. Then, in Section 3, we describe the studies reviewed here. Section 4 presents a comparative analysis of the studies, in order to identify areas of agreement, and of inconsistency. This then forms the basis for a discussion of future prospects, in Section 5. Our conclusions are summarised in Section 6.

2. Background

Aircraft emit a number of pollutants, of which three—CO_2, NO*x*, and noise—have received most attention to date. This section reviews production mechanisms and historical trends for each in turn.

2.1. Carbon dioxide

CO_2 has only been viewed as a pollutant since its recognition as the dominant greenhouse gas responsible for global warming. For a given fuel type, the amount emitted is directly proportional to the mass of fuel burnt. As fuel-burn is a key component of aircraft operating cost, economic considerations have driven significant reductions in aircraft CO_2 emissions since the beginning of the jet era. Fig. 1 demonstrates these gains, but also shows that the most dramatic improvements were achieved early on. The ACARE and NASA goals of further reductions in excess of 50% thus require a major departure from straightforward extrapolation of present-day trends.

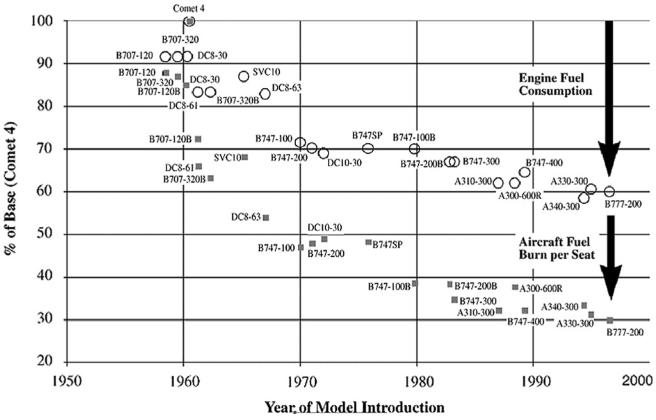

Fig. 1. Historical data on aircraft fuel-burn (Henderson and Wickrama, 1999).

To understand how aircraft technology affects fuel-burn, we consider the classical range equation (Torenbeek, 1997). For an idealised cruise, with aircraft operating parameters fixed, it can be arranged to give the following expression for the fuel consumption per payload-range:

$$\frac{W_f}{RW_p} = \frac{1}{R}\left(1 + \frac{W_e}{W_p}\right)\left[\exp\left(\frac{R}{H\eta L/D}\right) - 1\right], \tag{1}$$

in which R is the range, W_f the weight of the fuel burnt, W_p the payload weight, W_e the aircraft empty weight, η the engine efficiency and L/D the ratio of lift to drag. The parameter H represents the intrinsic energy content of the fuel; for kerosene it takes the value 4350 km. For a given range and payload, improvements in aircraft aerodynamics, engine performance and structural weight will decrease the amount of fuel burnt per passenger-kilometre, through an increase in L/D, an increase in η, and a decrease in W_e respectively. As the lift of an aircraft in cruise is equal to its weight, the first of these is equivalent to a reduction in drag. This quantity consists of two components: the zero-lift drag, which is largely due to friction between the aircraft skin and the flow, and the lift-dependent drag, which is dominated by the 'induced drag' associated with wasted kinetic energy in the aircraft's wake. Induced drag depends on the 'aspect ratio' of the wing; it is reduced when the span is increased.

The parametric dependence of Eq. (1) is even clearer if the argument of the exponential is small, in which case it can be simplified to

$$\frac{W_f}{RW_p} = \left(1 + \frac{W_e}{W_p}\right)\frac{1}{H\eta L/D}, \tag{2}$$

independent of the range. This represents an optimal limiting case in which the fuel required to carry the mission fuel becomes negligible. The value given by the exact expression, (1), is always greater than this, and becomes significantly so for greater ranges; long-range aircraft have an inherent tendency to be less efficient than short-range aircraft. For this reason, Green (2002) has proposed that future long-haul air travel should be organised in stages of no longer than 7500 km (4050 nmi), using aircraft specifically designed for this distance.

In practice, an aircraft also consumes fuel in reaching its cruising altitude, and this component becomes significant at very short ranges. Its influence can be seen in Fig. 2, which shows results for representative aircraft from the turboprop, regional-jet, narrow-body and wide-body categories (Vera Morales et al., 2011). The turboprop and regional jet only approach their best fuel

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