Chapter 12

AIRPLANES

1. Summary

The U.S. National Air Transport System handles two distinct segments of air transport movement: civilian (passengers and cargo) and military air transport. On an energy basis, commercial jetliners are forecasted to consume 86.5% of aviation fuel by 2025, with military aviation consuming nearly the balance, or some 13.5%. This analysis focuses on commercial passenger jet fuel usage and applies the results from that usage to cargo and military air transport.

We find that the instantaneous 2025 technical potential for savings with *State of the Art* technologies fully deployed in the stock is 2.25 quads, or 45.2% of EIA 2025 forecasted use of jet-A fuel. Capitalizing the incremental costs of these savings at a 5% real financing cost and over the 25-year period that an aircraft generally serves as a passenger carrier (serving an additional 15–25 years as a cargo carrier), these savings would be realized at an average cost of between $0.39 and $0.46 per gallon of jet fuel (before exact energy- and value-chain adjustments necessary to convert this from crude oil). The difference arises from different cost growth rate assumptions and number of active aircraft in 2025. This potential excludes further savings from hydrogen-powered aircraft, mainly due to major uncertainty within the timeframe of this analysis over capital cost and availability of this technology.

With *Conventional Wisdom* technologies, the corresponding savings are about 1.06 quads, or some 21.4% of EIA forecasted 2025 use (from *Annual Energy Outlook 2004*, hereinafter *AEO04*), at a cost of between $0.61/gal and $0.74/gal of jet fuel, and again before energy- and value-chain adjustments.

The main text incorporates the exact energy- and value-chain adjustments to a per-barrel-of-crude-oil basis. We note that these savings are instantaneous potentials and that they do not account for stock turnover. Stock turnover is treated separately in the main text and in *Technical Annex,* Ch. 21.

Overview of results

With *full and instantaneous deployment of* State of the Art *technologies*, we find 2025 technical potential savings of about 2.25 quads of jet fuel, or 45.2% of the *AEO04* 2025 baseline use. This figure agrees very well with the overall and individual technical findings in [1], [7], [13], [14], [15], [16], [20], and [25]. The savings are available at a cost of saved fuel of between $0.39/gal and $0.46/gal, projected from [1], [7], [9], [10], [11], [19], [20], [24], and [30], and using the methodology detailed below. The saved energy would cost somewhere between $9 and $12 per barrel of saved crude, after eliminating costs of non-efficiency measures, and after approximate energy- and crude-to-jet-A fuel value-chain adjustments. We have not included a rebound effect as we expect most of the monetary savings to be retained by the airlines given their poor medium-term financial outlook (at least collectively if not always individually).

For the commercial fleet only, the savings equate to 10.2 billion gallons. This incorporates the gain in seats per aircraft vs. EIA 2025. The saved fuel works out to a simple average of between 758,000 and 871,000 gallons per aircraft per year in 2025 using EIA's and RMI's aircraft projections, respectively. The latter figure is derived from incorporation of about 12.9% fewer aircraft into the active fleet due to the increase in seats per aircraft above EIA's assumptions. For *State of the Art* technologies we assign a more conservative 25% of the total real incremental cost of modern aircraft as the nonefficiency related investment portion. At the 25-year expected life for passenger aircraft, the annual capital recovery factor at our assumed 5% real discount rate equates to 7.10% of the up-front capital cost. Deducting 25% of the total aircraft cost-increases as non-efficiency related technology costs, we have a simple average annualized capital cost of between $300,000 and $350,000 per aircraft—representing less than half of the $758,000 to $871,000 value of annual saved fuel if the average departure-gate price of jet-A fuel were $1.00/gal. The findings are summarized in Tables 12-1 and 12-2 below:

Summary Table **Aircraft Fuel Savings and Incremental Costs:** **Effects at Instantaneous Potential and with Turnover**	**Impact of Technology Portfolios**	
	***CW* Fuel redc'n & cost**	***SOA* Fuel redc'n & cost**
Fuel Savings: Total stock (including military & cargo)		
Instantaneous Potential	21.4%	45.2%
Coherent Mobilization (I.e., with stock turnover)	8.4%	9.9%
Costs (Per Aircraft Basis, Average of low and high estimates)		
Cost of saved energy ($/gal jet fuel)	$ 0.67	$ 0.46
Before energy & value-chain adj ($/bbl jet fuel)	$ 28.31	$ 19.27

Table 12-1 Summary of RMI's Cost of Saved Energy (CSE) calculations for airplanes.

Background Detail Table **Aircraft Fuel Savings and Incremental Costs** **Due to Technology Improvements**	**Year 2000 Baseline**	**Impact of Technology Portfolios**			
		***Conventional Wisdom* Technologies**		***State of the Art* Technologies**	
Fuel Savings		**2025**	**Fuel redc'n (%)**	**2025**	**Fuel redc'n (%)**
Commercial Passenger Stock					
AEO2004 baseline stock fuel use implied from SMPG (Quads)	2.23	3.06		3.06	
Instantaneous Potential Fuel Use (Quadrillion Btu)		2.41		1.68	
Savings in commercial stock (Quads)		0.66	21.4%	1.38	45.2%
AEO2004 2025 implied baseline stock fuel use (M gal)		22,683		22,683	
Instantaneous Potential Fuel Use (M gal)		17,831		12,437	
Instantaneous Potential Fuel Saving, (M gal)		4,852	21.4%	10,246	45.2%
Instantaneous Potential Fuel Saving, per avg AEO ac-yr (M gal)		0.359		0.758	
Instantaneous Potential Fuel Saving, per avg RMI ac-yr (M gal)		0.359		0.871	
Total Stock, including Military (13.5% of use) and Cargo (26.5%)					
AEO2004 baseline stock fuel use implied from SMPG (Quads)	3.62	4.97		4.97	
Instantaneous Potential Fuel Use (Quadrillion Btu)		3.91		2.73	
Savings in commercial stock (Quads)		1.06	21.4%	2.25	45.2%
AEO2004 2025 implied baseline stock fuel use (M gal)		36,846		36,846	
Instantaneous Potential Fuel Use (M gal)		28,964		20,203	
Instantaneous Potential Fuel Saving, (M gal)		7,881	21.4%	16,643	45.2%
Instantaneous Potential Fuel Saving, per avg AEO ac-yr (M gal)		0.583		1.232	
Instantaneous Potential Fuel Saving, per avg RMI ac-yr (M gal)		0.670		1.415	
Costs (Per Aircraft Basis)		**2025 Low**	**2025 High**	**2025 Low**	**2025 High**
Annual overall incremental ac cost growth rate (incl. non-eff techn)		0.25%	0.30%	0.30%	0.35%
Average cost per aircraft (2000$, M)	$ 71.60	$ 76.21	$ 77.17	$ 77.17	$ 78.14
Gross ac cost increment (2000$, M)		$ 4.61	$ 5.57	$ 5.57	$ 6.54
Annualized cost (2000$, M)		$ 0.33	$ 0.40	$ 0.40	$ 0.46
Share of cost due to efficiency		67%	67%	75%	75%
Net (efficiency only) Annualized Cost (2000$, M)		$ 0.22	$ 0.26	$ 0.30	$ 0.35
Cost of saved energy ($/gal jet fuel)		$ 0.61	$ 0.74	$ 0.39	$ 0.46
Net of engy & value-chain adj ($/bbl crude)		$ 18.50	$ 23.94	$ 9.06	$ 11.97

Table 12-2 Details of RMI's Cost of Saved Energy calculations for airplanes.

With *Conventional Wisdom* technologies, the instantaneous technical potential savings are about 1.06 quads of jet fuel, or 21.4% of the *AEO04* 2025 baseline, at a cost of the saved fuel of between $0.61/gal and $0.74/gal, or somewhere between $18 and $24 per barrel of crude after approximate energy- and value-chain adjustments. Here we assume that as much as 1/3 of the real incremental costs are derived from the nonefficiency related investment portion. We also assume little change in the number of seats per aircraft, so that RMI's active 2025 stock is equal to that of EIA.

Overview of methodology

Defining the technology space: We incorporate advanced versions of airframe shape, airplane propulsion systems, propulsion-airframe integration (PAI) technologies, and system and logistics technologies. We do not incorporate hydrogen propulsion into our *State of the Art* technology considerations. We use the two key parameters "minimum-flight-hours-to-block-hours" and "load factor" to assess the Air Traffic Management and operations efficiencies together with the mechanical efficiency improvement of aircraft. This allows for a system-level assessment of total fuel efficiency gains and associated cost changes. We assess each factor in a bottom-up model that also takes into consideration system-effects (see Chapter 12 Excel spreadsheets in the *Technical Annex* www.oilendgame.com).

The reasons why we have not considered liquid-hydrogen propulsion merit some attention before turning to other methodological topics. In essence, it boils down to incremental cost within the timeframe we consider here, 2025. That said, NASA, Boeing, a 35-partner EU consortium led by Airbus, and Tupolev (which flew a *Tu-154* fueled with liquid hydrogen in 1988) have done systems studies that established "cryoplanes'" basic feasibility, found surmountable design issues, and confirmed favorable inherent safety attributes. Several ongoing research projects for hydrogen-powered flight exist today; for example, Boeing has a small PEM fuel-cell demonstrator airplane and a target of a solid oxide fuel-cell APU (reforming jet-A fuel) onboard commercial aircraft by 2015 [2]. However, our best assessment is that liquid-hydrogen-powered aircraft may stretch costs to a level sufficiently high (and at this time also sufficiently uncertain, especially given the state of the industry's balance sheets) as to warrant excluding it from the set of options that will have significant impact within the timeframe of this study.[*]

In terms of efficiency gains, Airbus found that liquid-hydrogen airplanes would use 8–15% more fuel energy than their kerosene-fueled counterparts, but that conclusion seems outdated. Approximate analyses show that a further 4–5% efficiency gain would be possible [2] vs. a given nonhydrogen baseline counting only airframe performance—heavier empty weight, lighter takeoff weight, higher drag, higher initial cruise altitude capability and climb. But that doesn't include hydrogen's potential for greater engine efficiency. Integrating all these factors yields a ~10–15% net gain in tank-to-flight efficiency for a nominal *767* platform redesign [3], not including the other improvements in platform physics analyzed here for kerosene-fueled airplanes. Hydrogen liquefaction energy (from ~300 to 20 K including *ortho-para* separation) must be added, but can be

---

[*] This conclusion is driven largely by competition with the very efficient kerosene-fueled aircraft considered here, and tacitly assumes that other considerations, such as climate protection, don't accelerate commercialization of hydrogen aircraft. Nonetheless, given the current state of development in this area, there is little doubt that the technology *should* be included for estimates that explore the overall technical aviation fuel savings potential for years beyond 2025, at least for long-range aircraft.

straightforwardly reduced from today's standard ~11–15 kWh/kg (basically using 1960s technology) to just ~4–5 [4], equivalent to 12–15% of hydrogen's lower heating value. This would about cancel the airplane's efficiency gain, but unlike petroleum-based Jet-A fuel, the energy used could be renewable.

Dutch designer P.M. Peeters [5], pursuing earlier work by NASA's Chris Snyder [6], believes a liquid-hydrogen-fueled airplane using a lightweight fuel cell and electrically driven unducted fans, which could use lightweight superconducting motors, could double the tank-to-flight efficiency of the LH_2-turbofan airplanes normally analyzed. For example, his conceptual design for a long-haul 415-seat airplane on a 7,000-km flight at 0.75 load factor would use 55% less fuel energy than a comparable *747-400*, while his 145-seat conceptual design would use 68% less fuel energy on a 1,000-km flight at 0.70 load factor than a comparable *737-400*. Such savings could in principle make this approach attractive, particularly for short hauls, where the reduced airspeed assumed (Mach 0.65) would be far less important (10% rather than 23% increase in block time). Indeed, Peeters thinks it offers a ~20% long-haul and ~50% long-haul energy-saving potential beyond even "a highly efficient future design using advanced technology engines, aerodynamics and structures."

Savings across aviation categories: Of the 5.0 quad 2025 forecasted aviation fuel use, 4.3 quads or 86% is commercial jet fuel. Due to this high fraction of aviation fuel being consumed by commercial passenger and cargo transport, we have focused our analysis on this segment and we have assumed that its savings potential is approximately applicable to military aviation (13.5% of use) and aviation gasoline (<1% of use). We therefore apply the savings potential identified for commercial jet fuel to military and aviation gasoline fuel use. In so doing we implicitly assume that the U.S. Air Force is an early adopter of new aviation technologies. Military adoption is most straightforward in platforms that resemble civilian ones; the special requirements of unique tactical platforms are discussed further in *Technical Annex*, Ch. 13, but for present purposes, prorating on the fleet is an adequate approximation for this small term.

Calculation of savings potential: A reduction in use of jet-A fuel of 45.2% represents the sum of our estimates for *State of the Art* aircraft and system-level savings. Our estimated aircraft-specific savings amount to 35.1% off the *AEO04* 2025 baseline. We have obtained these savings by a bottom-up calculation of the impacts of various technologies on aircraft block-fuel use.

System-wide savings from improvements in the air transportation system of about 11% and logistical (i.e., load factor) improvements of 5% are expected to occur with respect to any given aircraft-specific baseline and versus the EIA projected demand for seat miles. Due to the largely IT-related costs of these savings, we expect them to occur at a net saving to the industry.

In sum, our 2025 *State of the Art* aircraft fully deployed into the stock with system-wide and logistical savings therefore give an overall technical potential for saving about 45.2% off the *AEO04* 2025 baseline aviation fuel use.

Calculation of efficiency-related technology costs: We find that these *State of the Art* aircraft-specific savings are achievable at an estimated average cost of 46¢ per gallon of saved jet fuel. We calculate this value by making a set of moderate assumptions around future aircraft costs, [7], [13]. We estimate costs of efficiency-improving technologies from forecasts of real aircraft acquisition costs. These forecasts indicate real costs will on average increase by 0.5% to 0.6% per year for the time horizon in this study. The forecasts of future cost increases incorporate historical trends and industry expert consensus forecasts.

Since improvements not related to efficiency are also included in the cost forecasts, we deduct the estimated costs of these, e.g., improvements in safety, quality, and amenity. We estimate that approximately 75% of acquisition costs can be attributed to improvements in fuel-economy, due to four main factors. These factors are the continued impacts of airline deregulation and also of low-cost airlines, fuel being the number two main cost line item after labor, and expected future environmental regulation.

Calculation of Cost of Saved Energy: To calculate the Cost of Saved Energy we first calculate fuel saved per flown seat-mile, incremental to that forecasted by NEMS/*AEO 2004*. To do this we invoke engineering scaling experiments to assume that the percent savings generated by deployment of efficiency-enhancing technologies continue to follow the approximate inter-segment proportions as calculated in recent NASA literature across the three major domestic and international commercial aircraft segments. This offers a total technical saving across the fleet of 20% on a block fuel use basis (i.e. on a fuel consumed basis) above the 23.4% already included for new aircraft in *AEO 2004* for 2025. We then assign a cost to that savings based on the above method. We assume the costs of the *SOA* 2025 aircraft is incorporated in the 2025 real acquisition cost of aircraft. This cost is expected to grow by 0.5% per year, or 0.375% per year for the efficiency-related technologies, to give an efficiency-related increase of approximately 9.8% by 2025. While marginal cost estimates for these technologies are difficult to calculate with any accuracy, aircraft R&D cost considerations and historical trends indicate that this average cost is fairly representative of the techno-economic savings, i.e. real historical savings have been realized based on adopting technologies with marginal costs below a threshold in the neighborhood of $1.00/gal.

2. Methodology

Estimating potential for fuel savings

To establish aircraft-specific technical efficiency potential for 2025, we identify potential fuel savings from improvements in technologies that impact overall aircraft energy use. We track effects separately, tally their impact, and deduct from the total the sum of all effects already incorporated in the *AEO04* baseline. For aircraft-specific technologies, we account for the impact of both individual technologies and for the effects of properly integrating them into the aircraft (propulsion-airframe integration).

We also consider technologies that impact national airspace system efficiencies, although estimates of the impacts are difficult to quantify with accuracy, so here we operate with a range. Gains from technologies that affect systemic efficiencies have historically also been offset by congestion effects, which we consider. The potential technologies and their associated savings are described in detail in the next two sections.

Estimating costs of efficiency-related technologies

In the absence of better alternatives, we estimate costs of efficiency-improving technologies from forecasts of real aircraft acquisition costs. This method of estimating costs incorporates historical trends and industry expert consensus. However, since costs of improvements not related to efficiency, e.g., safety, quality, amenity, are also included in these forecasts, we adjust the improvement costs in an approximate fashion. We target a conservative (small) adjustment, and we base its magnitude on noting that the majority of improvements in one way or another probably will be related to fuel-economy. This relationship arises because of pressures due to four main factors: (1) expected continued impacts from airline deregulation, (2) additional competition from low-cost airlines, (3) fuel costs being the number two cost line item after labor, and (4) expected future environmental regulation. In sum, these make it reasonable to assume that a majority of the cost increases for future aircraft development efforts will focus on improving aircraft energy efficiency. We have therefore conservatively assumed that 1/3 of these costs will be directly attributable to improvements in safety, quality, and amenities, and that the remaining 2/3 of the forecasted aircraft costs represent costs of energy-saving technologies.

Historically, the data show a monotonic decline in fuel use per seat mile. A 70% reduction in block fuel use was observed in the 40 years from 1960 to 2000. In the same period, real acquisition cost increased 0.8–0.9% per year. Operating costs per revenue passenger mile declined 65% in real terms. A 40% reduction in block fuel use was seen in the 30 years to 2000, and a 15% improvement in the 15 years to 2000 [14, Figure 2.1.1, p. 3]. In intervening periods, a 38% reduction in the 20 years from 1960 to 1979 was also observed, with another 31% in the next 20 years to 1999 (or a 50% reduction vs. the 1979 baseline).

Going forward: To 2050, a further 18% reduction vs. the 1960 baseline block fuel use is expected, i.e. a 58% improvement over the 1999 baseline [7, Figures 6.4, 6.5, p. 124]. Real acquisition cost growth is expected to level somewhat to about 0.5–0.6%/y over the next 50 years [7, Figure 6.7, p.125, 1995$]. While historical operating costs per revenue passenger mile declined 65% in real terms in the 40 years to 2000, these costs are expected to continue the decline by another 45–60% in the years to 2025–30 [7, Figure 6.6, p.125, 1995$]. Some studies expect BWB (Blended-wing-body) direct operating cost (these include amortization of aircraft lease) on a seat-mile basis will be 10–19% below that of a current *747-400* [8].

In sum: Based on these analyses of past and future aircraft cost trends, we have assumed that incremental costs associated with the findings for projected fuel reduction will be amortized at current RD&D budget allocation levels among the competing manufacturers in the jet engine, materials, and vehicle-design and assembly segments, and that it will follow the growth path expected in the literature.

We also assume that one of several possible small discontinuities will actually occur, either as Airbus and others predict on the airframe materials front, or from other areas, e.g., a result of intensified engine technology R&D efforts giving higher SFC reductions than the historical 20% reduction; or if operating barriers associated with laminar flow control are overcome, a greater than the projected 20% increase in the lift/rag ratio (L/D) may be feasible.

We have therefore used 0.25–0.30% as a likely annual growth of per-unit commercial aircraft costs 2000–25 with *Conventional Wisdom* technologies. This implies that real costs will increase by approximately 6.4–7.8% by 2025. We assume 2/3 of this increase is attributable to energy-saving technologies. For *State of the Art* technology developments, we assume an annual growth rate of 0.30% in the low case and 0.35% in the high case, and that 75% of this growth is attributable to energy-efficiency technologies' incremental costs.

Domestic U.S. sales in 2002, the last pre-9/11 "normal" year, were 379 commercial jetliner aircraft, worth a total of $28.1 billion, or $27.1b in 2000 $, for an average price per aircraft of $71.6 million [9].

Calculating the Cost of Saved Energy: We first calculate fuel saved per flown seat-mile above that forecasted by NEMS/*AEO 2004.* Next we invoke engineering scaling experiments and assume that the percent savings generated by deployment of efficiency-enhancing technologies are approximately the same across the three major domestic and international commercial aircraft segments. This makes for a total technical savings across the fleet of 20% on a block fuel use basis (i.e., on a fuel consumed basis) above what is included for new aircraft in *AEO04* 2025.

We also expect air transport system benefits to proceed and we find that a 5.1% reduction in block fuel use due to conventional Air Traffic Management technologies is likely, and that a 3.5% reduction will result from technologies that improve load factor.

We then assign a cost to that savings based on the above method. We assume the costs of the *SOA* 2025 aircraft is incorporated in the 2025 real acquisition cost of aircraft.

Importance of aircraft design

An aircraft is an excellent example of a clearly defined and self-sustained system where *interaction effects make significant impacts on total system efficiency*. As a result, an integrated approach to whole-systems design for aircraft is of the highest importance.

While on a stand-alone basis a given engine may be superefficient compared to any alternative engine, the full effect of the superefficient engine will for many reasons not transfer directly to the airplane unless the engine is properly integrated into the airframe. This integration therefore plays a very important role in determining the ultimate fuel efficiency of the airplane. In other words, upgrading the engine on an existing aircraft to a more fuel-efficient engine will achieve only a fraction of the potential fuel efficiency gains.

Because an aircraft is a self-sustained system once it is airborne, if the maximum benefits from the engine improvement are to be realized, then the airframe itself must be redesigned to reap the full benefits from an improved engine. In turn, airframe redesign could either involve a redesign of hull shape and configurations using existing airframe technology, or could additionally involve new advances in materials and airframe component technology *prior* to redesign of airframe shape and structure.

As such, incremental aircraft fuel efficiency gains depend on whether only the engine is replaced, whether advanced airframe technology is added, and on whether the airframe is designed to fit the efficient engine. Moreover, it also depends on whether aircraft auxiliary power needs can be reduced—if so, further efficiency improvements arise for the same reason: less in-flight fuel use results in decreased need for onboard storage, both directly and via mass decompounding (less fuel to carry less fuel).

An example will illustrate the value of a whole-systems approach to aircraft design. When using Ultra-Efficient Engine Technology (UEET), the wing need not be designed to carry as much fuel and so the volume—therefore the weight—of the aluminum wing can be reduced to further reduce fuel use. This change amounts to a direct change in the airframe design due to the improved engine efficiency. Next, manufacturing the wing from lightweight carbon composite materials instead of from aluminum will further reduce the weight of the wing, assuming constant wing size and mechanical performance. However, because the mass of an identically matching composite wing would be smaller, this smaller mass will further reduce in-flight fuel need, and will therefore translate into a wing mass-reduction additional to that resulting from the improved engine efficiency. Although this is a second-order (smaller) effect, using lightweight carbon-composites rather than aluminum for wing design requires even less fuel to be carried, which permits an even smaller wing.

As a practical result, several design iterations are required to optimally size an engine for an aircraft, and vice versa. First, the performance for an airplane and the resulting engine is estimated. Then the engine requirements are passed on to the engine supplier. Second, the airplane is configured with the supplied engines, before the airplane performance is checked to see if it meets the given performance requirements. The engines are then adjusted to enable the airplane to meet the performance requirements. Standard practice is to then again re-design the airplane for the final engines, before it is offered for sale and construction.

However, while the bulk of the weight-optimization is achieved during the first few iterations, significant additional benefit does accrue from repeating the procedure several more times, see [10, p. 17] and Figures 6-8 and 6-9 in [11, p. 130]. These Figures powerfully illustrate the convergence history for Multidisciplinary Design Optimization (MDO) of entire Blended-Wing-Body aircraft. In particular, they illustrate (1) the lower mass achieved using distributed rather than conventional propulsion (reductions of 5.8% TOGW (takeoff gross weights) and 7.8% fuel weight) achieved by cycles of redesign from increased propulsive efficiency (from ‘filling the wake’), lower trailing edge induced drag, and elimination of traditional flaps, and (2) the significant impact from design-iterations on aircraft gross mass reduction [10, p. 17]. For example, Boeing claims that its new *7E7* will offer 20-percent better fuel efficiency than the comparably sized *767-300*: 8% is from new engine technology; 6% from new airframe materials, aerodynamics, and systems architecture; and the remaining 6% from “cycling the design,” i.e., the added efficiency of the proposed new engines and airframe design allows the airplane to carry less fuel, thereby optimizing the requirements for the size of the wing and landing gear to achieve even more efficiency [12].

3. Instantaneous technical potential and costs of saving aircraft fuel

Summary

For the *Conventional Wisdom* technology portfolio we rely on incremental improvements that can be done to the traditional tube-and-wing aircraft configuration. For a *State of the Art* portfolio, we rely on a Blended-Wing-Body (BWB) hull shape and further Air Traffic Management and load factor improvements. The aerodynamic benefits from the BWB configuration are significant. Overall we obtain estimates of costs and savings that are in line with the literature.

We have not incorporated deployment of hydrogen-powered aircraft. Technically this *is* a feasible option within our time horizon, yet on balancing the evidence we view it as an option that within the timeframe of this study would very likely stretch the costs to a level sufficiently high to warrant its exclusion, even if it were available. The uncertainties around the costs of the planes and the associated infrastructure changes and fuel are also substantial. There is also considerable uncertainty around availability itself. We would like to note, however, that hydrogen-powered aircraft would, due to ~70% reduction in fuel weight for routes above ~3,000–5,000 nautical miles (where the mass compounding of jet-A fuel becomes large), probably make a significant impact on the long-haul segment. While uneconomical for some time to come, we believe the technology *should* be included in estimates that explore the technical potential for years after 2025.

Estimating fuel use reduction potentials and system-level gains

A Graphical Computer Aided Sizing and Optimization System (GCASES), developed by the McDonnell Douglas Company, was utilized in [13], and we rely on the results from this model and the output from model runs in [13], and analyses in [14], [15], and [16] for benchmarks and estimates of aircraft fuel efficiency. GCASES is an interactive program that combines interdisciplinary modules to rapidly iterate to a configuration that satisfies all of the specified performance requirements. The Phantom Works Huntington Beach (PWHB) team calibrated GCASES to match the baseline BCA sized configuration.

In addition to the aircraft-specific technology components identified and simulated in [13] and [14], we incorporate estimates of impacts on commercial aircraft fuel use achievable through nontraditional aircraft designs and system-level measures. For *State of the Art* aircraft design we incorporate the Blended-Wing-Body system (BWB, or “flying wing”) concept, [15], [16]. We also include estimates of the effects of optimizing flight trajectories via both so-called free flight and via other air traffic flow pattern measures, e.g., improved ground/air delay-exchange and improved accuracy of the probability associated with weather prediction to improve predictability of air traffic movement in the National Airspace System.

Conventional Wisdom technologies and costs of saved fuel

Aircraft-specific technologies: An aircraft can be designed to optimize one of several performance factors (weight, speed, altitude, climb, fuel efficiency, cost, etc.). We assume *Conventional Wisdom* technologies will continue improvements of the traditional tube and wing aircraft design. The baseline aircraft used in [13] and [14] were modified by integrating advanced UEET engines of varying Bypass Ratios (BPR) and diameters to minimize the resulting economic costs, a measure which closely follows fuel efficiency. General Electric (GE) and Pratt & Whitney (P&W) UEET engine designs bounded the region that was expected to provide the optimum BPR for each technology by 2010. The sizing drivers and integration issues listed in Table 3.1 of [13, p. 26] were used for the six study UEET engines that were installed on the baseline study airplane.

The performance evaluation included the assessment of the overall airplane system attributes including weight, drag, noise, emissions, mission fuel use and operating cost. In terms of weight, advanced materials developments are critical, and studies cite specific and general findings. For example, a hybrid titanium/carbon-composite turbofan disk can save >20% of mass compared to the usual monolithic titanium disk (hybrid fan blades also being developed) [17]. More generally, carbon-composite fuselage programs are predicted to cost significantly *less* than their metal counterparts. Airbus aims to save 30%

of weight *and* 40% of cost while eliminating structural fatigue and corrosion (for easy maintenance) and improving passenger comfort [18]. While this study is broadly encouraging, the Airbus authors find it is too early to conclude, as validation is scheduled for 2007. However, the cost reduction estimates appear to agree with other and similar studies, e.g., a Lockheed-Martin Skunk Works project summarized to a panel of the Defense Science Board, [19], [20], where a conceptual 95% carbon-composite advanced tactical fighter airframe design was 1/3 lighter (i.e., about 12–15% TOGW and 23% fuel burn reduction for a given mission), yet 2/3 cheaper than its 72%-metal predecessor. We incorporate these estimates into an overall assessment of weight reduction potential for conventional tube and wing aircraft by 2025.

Fuel-use reductions from *Conventional Wisdom* aircraft technologies: For context, historical trends of block fuel use fell by ~70% during 1960–2000, a 1.3% annual decrease [14, Figure 2.1.1, p. 3]; by ~40% in the 30 years to 2000, or 1.2%/y; and by 15% in the 15 years to 2000, or 0.9%/y [14, Figure 2.1.1, p. 3].

For this portfolio we assume improvements in engine and aerodynamic technologies will occur at the rates found in general industry projections, congregating around 20% to 30% improvement in SFC and 20% in L/D by 2050 [7, pp. 104–105], or approximately half of that by 2025. As a 1% improvement in SFC, L/D, and W (weight) gives a 1%, 1%, and 0.7% reduction in fuel burn per rpm respectively; improvements of 10–15%, 10%, and 30% by 2025 would be expected to reduce fuel burn per rpm by 41–46%. We have assumed unchanged ratios of ground-time and flight-time efficiencies (airborne hours to block hours and minimum flight hours to airborne hours), both expected to remain at 0.85 [7, p 107], and we have assumed that 98% of fuel is burned while airborne.

Conventional Wisdom Tech Portfolio Summary of Impacts	Aircraft model	Scaling %	Improvement in block fuel use vs. previous %	Reduction in block fuel use vs. baseline %	NEMS 2000 seat-miles per gallon SMPG	Assumed seats	Assumed journey length mi	Aircraft MPG mi/gal	Inferred NEMS block fuel use gal	New block fuel use gal	Implied 2025 RMI seat-miles per gallon SMPG	Implied improvement in SMPG %
Wide Body												
(1) Large												
Baseline (tube-and-wing)	*747-400*			0.0%	61.6	420	3453	0.15	23,544			0.0%
w/ UEET				12.9%		420	3453	0.17		20,507	70.7	14.8%
w/ UEET & Prop Airfr Integr (PAI) 2010				30.6%		420	3453	0.21		16,339	88.8	44.1%
w/ UEET & Prop Airfr Integr (PAI) 2025			20.7%	45.0%		420	3453	0.27		12,957	111.9	81.7%
(2) Medium												
Baseline (tube-and-wing)	*777-200ER*			0.0%	61.6	305	3453	0.20	17,097			0.0%
w/ UEET				10.2%		305	3453	0.22		15,353	68.6	11.4%
w/ UEET & Prop Airfr Integr (PAI) 2010				27.0%		305	3453	0.28		12,481	84.4	37.0%
w/ UEET & Prop Airfr Integr (PAI) 2025			18.3%	40.3%		305	3453	0.34		10,201	103.2	67.6%
(3) Wt Avg of Lg + Med	Wide-Body Wt Avg			41.8%	61.6	340					105.9	71.9%
Narrow-Body												
Baseline (tube-and-wing)	*737-800*			0.0%	63.2	162	1151	0.39	2,950			0.0%
w/ UEET				3.1%		162	1151	0.40		2,859	65.2	3.2%
w/ UEET & Prop Airfr Integr (PAI) 2010				19.1%		162	1151	0.48		2,387	78.1	23.6%
w/ UEET & Prop Airfr Integr (PAI) 2025			12.9%	29.6%		162	1151	0.55		2,078	89.7	42.0%
Regional Jets												
Baseline (tube-and-wing)	Pass-scaled w/ *737-800*			0.0%	41.7	70	576	0.60	966		41.7	0.0%
w/ UEET				3.1%		70	576	0.61		936	43.0	3.2%
w/ UEET & Prop Airfr Integr (PAI) 2010				19.1%		70	576	0.74		782	51.5	23.6%
w/ UEET & Prop Airfr Integr (PAI) 2025			12.9%	29.6%		70	576	0.85		681	59.2	42.0%
Weighted average												
Harmonic weighted by active aircraft vs. no techn.				31.0%	59.3						78.4	32.2%
Harmonic weighted by active aircraft vs. AEO 2004				14.2%								22.3%
System Savings (ATM & Load Factor)												
ATM-related savings (block fuel savings) vs. AEO 2004			5.1%	18.5%								
Load factor improvement (block fuel savings) vs AEO 2004			3.5%	21.4%								
Fuel savings, total stock (Quads)				1.06								

Table 12-3 Summary of *Conventional Wisdom* technology portfolio

In a separate study, results in [14] combine these *Conventional Wisdom* technologies in a way that deals with the integration issues. The results show that UEET engines installed in airframes resized to benefit from the reduced specific fuel consumption and weight could lead to between 19.1% and 30.6% reductions in block fuel use by 2010 vs. corresponding baseline aircraft types. The three baseline types that were investigated were small (*737-800* class), medium (*777-200ER* class), and large (*747-400* class) aircraft. Respective block fuel use reductions due to UEET and Propulsion-Airframe Integration (PAI) for these traditional tube-and-wing aircraft classes were 19.1%, 27.0%, and 30.6% [14, Fig. 4-3-1, p. 25]. These results were assumed achievable by 2010. Good agreement therefore exists between the magnitudes of these technology reductions and the given time horizons, and we have applied these improvements and projections about further developments based on historical trends and other studies to obtain estimates for achievable improvements due to *Conventional Wisdom* technologies by 2025.

Finally, real operating costs are expected to drop by another 45–60% in the years to 2025–30 [7, Figure 6.6, p.125, 1995$], or some 1.2% to 1.6% annually vs. the 1995 baseline. While operating costs comprise categories other than fuel, we assume this cost category is a good proxy for fuel use. Also, given recent advances in lightweighting, such as the 7% efficiency-gain from lighter weight embedded in the *7E7*, we assume that *Conventional Wisdom* technology progress will proceed at the lower end of the operating cost savings, i.e., about 1.25% annually or 20.7% over 15 years. This makes for a total of 45.0% reduction in block fuel use for large aircraft by 2025 *versus* the 2000 vintage baseline widebody *747-400*. We then scale this percentage to the other aircraft by adding to their improvement potential the simple difference between the large (*747*) aircraft 2010 forecast of 30.6% and 45%, i.e., 14.4%, after scaling this difference by the ratio of the overall improvement for a given aircraft type to the large aircraft in 2010. For example, the *777-200ER* had achieved a 27.0% improvement by 2010 relative to 2000, so

(27.0/30.6) × 20.7% = an 18.3% *777-200ER* block fuel improvement between 2010 and 2025, for an overall block fuel improvement for the *777-200ER* of 40.3% from 2000 to 2025.

Respective block fuel use reductions assumed achievable by 2025 due to UEET and Propulsion-Airframe Integration (PAI) for traditional tube-and-wing aircraft classes were therefore 29.6% (both Regional and Narrow-body *737*), 40.3% (Widebody *777*), and 45.0% (widebody *747*), for a 41.8% weighted average gain for the widebody class, and an harmonic average (weighted by active aircraft) of 31.0% block fuel reduction versus the 2000 EIA *AEO04* baseline, or 14.2% reduction versus the 2025 EIA baseline, before system effects. This moves the seat-miles per gallon for the active stock from 59.3 to 78.4. In light of [14, Fig. 4-3-1, p. 25] this implies a flattening after 2008, the year in which the near-50% carbon composites *7E7* will be operational [21], i.e., the figures are in line with previous eras in aviation efficiency development.

Fuel use reductions from Air Traffic Management gains: The efficiency in Air Traffic Management (ATM) and aircraft operations are commonly assessed through two parameters: ‘minimum-flight-hours-to-block-hours’ and load factor. Increasing the former ratio reduces the fuel consumed during non-cruise, non-ideal flight segments. Increasing the load factor improves fuel burn per rpm and reduces the ratio of Direct Operating Costs (DOC) to rpm. Combining the improvement potentials for these parameters of ATM and operations with the mechanical efficiency improvement of aircraft allows for system-level assessment of total fuel efficiency gains and resulting cost changes for future aircraft systems. Savings potential and costs are difficult at best to estimate from ATM-related technologies.

Given the technical similarity between the *Conventional Wisdom* ATM technology portfolio and the *State of the Art* portfolio, we have left the ATM discussion as a separate topic towards the end of this section. The difference between the two is essentially related to their deployment penetration. We rely on Eurocontrol and FAA estimates for *Conventional Wisdom* technologies for improving ATM. These organizations expect ATM to save 5% of the fuel incremental to EIA 2004. This contrasts with [7, pp. 107–108], where all gains from ATM are assumed to follow the historical norm of becoming subsumed by traffic flow increases and associated delays. Costs are very difficult to estimate, so we have assigned these at an average cost approximately equal to the portion of all non-ATM related *Conventional Wisdom* technologies.

Load factor: Load factor increased by 20 percentage points from 1971 to 1998 [7, p 108], reaching today’s level of over 0.7. According to [22], load factors of 0.9 are feasible through advanced bookings and use of an optimal size of aircraft. However, early-morning and late-night flights with many empty seats and airport infrastructure and airspace congestion will tend to lower the efficiency of hub-and-spoke systems, and will significantly limit the upper bound of such an improvement in average load factor.

Airbus projects that load factors will continue its recent historical trend and increase only by 3.3 percentage points to about 74.3% by 2022 [23], or 0.17% per year. This contrasts to EIA 2004, which on a harmonic average basis expects load factor to be 76.2% in 2025. Applying a cost equivalent to that of ATM (average non-ATM CSE), we use a load factor growth of 0.17% per year in our *Conventional Wisdom* technology portfolio and 0.25% in the *State of the Art* portfolio. This gives 79.0% and 80.3% load factor, respectively, or a drop in seat-miles demanded of 3.5% and 5.1% respectively.

Cost of technologies: Historical aircraft acquisition costs grew 0.8–0.9% per year on a real per-unit basis during 1960–2000. Looking forward, the annual unit cost growth rates are expected to moderate to about 0.5–0.6% over the next 50 years [7, p. 112 and Figure 6.7, p.125, 1995$]. With regards to materials, advances have been relatively inexpensive, and we assume they will occur at half of historical aircraft real acquisition cost increases. In this regard we note that the first 50 models of the *7E7* appear to be selling at a price approximately equal to that of aircraft competing in this seat-segment [21; about $120M each, or $6b in total; sale to All Nippon Airways, see (9) for comparison]. Given that several sources expect airframe costs to decrease substantially, Airbus by 40%, and given that these expectations are based on deployment of carbon composite airframes—materials that were only modestly included in the originally expected growth rates (5–7.5% weight reduction by 2025, [7, p. 106])—we adjust the cost growth rates downward to account for the differences in materials costs, but assume that the net cost of airframe, engines, and integration will remain positive.

In effect, for *Conventional Wisdom* technologies we assume that one of several possible small technology discontinuities will actually occur, either as Airbus and others predict on the airframe materials front, or from other areas, e.g., a result of intensified engine technology R&D efforts giving higher SFC (specific fuel consumption) reductions than the historical 20% reduction, or if operating barriers associated with laminar flow control are overcome, a greater than the projected 20% increase in the lift/drag ratio (L/D) may be feasible. We have therefore used 0.25–0.30% as a more likely annual growth of per-unit commercial aircraft costs 2000–25 with *Conventional Wisdom* technologies.

To formulate our average aircraft cost baseline, we note that domestic U.S. sales in 2002, the last pre-9/11 “normal” year, were 379 commercial jetliner aircraft, worth a total of $28.1b, or $27.1b in 2000$, for an average price per aircraft of $71.6M [24]. The per-unit acquisition growth rate would therefore imply real incremental price rises by 2025 of between $4.61M and $5.57M in 2000 $.

Cost of Saved Energy for *Conventional Wisdom* technologies: A 2025 block fuel use reduction of 21.4% including system effects versus EIA 2025 baseline represents 1.06 quads of saved fuel across the active stock. Scaled to the commercial passenger fleet only, this becomes 4.9b gallons, or 359,000 gallons per 2025 aircraft-year. At a 25-year expected passenger aircraft life, the annual capital recovery factor at our 5%/y real discount rate is 7.10% of the up-front capital cost, leaving the annualized capital cost between $0.33M and $0.40M before deducting non-efficiency related investments.

The question as to what percentage of this annual cost should actually be assigned to fuel efficiency improvement is difficult to answer, but given the rise of onboard amenities and performance enhancements through design developments, approximately one third of the real incremental *Conventional Wisdom* technology costs might plausibly be accounted for as a non-efficiency related investment portion, leaving the annual cost of per-unit efficiency at between \$0.22M and \$0.26M. This leaves the cost of the saved fuel between \$0.61/gal and \$0.74/gal jet fuel, or between \$18.50 and \$23.94 per barrel of crude after energy- and value-chain adjustments.

State of the Art technologies and costs of saved fuel

Summary of aircraft-specific technologies considered: Similar to the analysis of *Conventional Wisdom* technologies, we first estimate the savings potential from *State of the Art* technologies within the 2010 timeframe. Next, we apply a level of progress between 2010 and 2025 that corresponds in magnitude to that found for *Conventional Wisdom* technologies. We summarize the instantaneous impact in Table 12–4.

***State of the Art* Tech Portfolio Summary of Impacts**	**Aircraft model**	**Scaling %**	**Improvement in block fuel use vs. previous %**	**Reduction in block fuel use vs. baseline %**	**NEMS 2000 seat-miles per gallon SMPG**	**Assumed seats**	**Assumed journey length mi**	**Aircraft MPG mi/gal**	**Inferred NEMS block fuel use gal**	**New block fuel use gal**	**Implied 2025 RMI seat-miles per gallon SMPG**	**Implied improvement in SMPG %**
Large BWB subst widebody [From Boeing/NASA]												
Baseline (tube-and-wing)	*747-400*			0.0%	61.6	420	3453	0.15		23,544	61.6	0.0%
BWB (Blended Wing-Body)	*450-1L*		20.0%	20.0%		468	3453	0.18		18,835	85.8	39.3%
BWB UEET	*450-1U*		24.0%	39.2%		468	3453	0.24		14,315	112.9	83.3%
BWB UEET w/ BLI & AFC	*450-1U* BLI AFC		5.5%	42.5%		468	3453	0.26		13,527	119.5	93.9%
BWB UEET w/ BLI, AFC, & Distr EWP 2010	*450-1U* BLI AFC DEWP		3.9%	44.8%		468	3453	0.27		13,000	124.3	101.8%
BWB UEET w/ BLI, AFC, & Distr EWP 2025	*450-1U* BLI AFC DEWP		20.7%	56.2%		468	3453	0.33		10,309	156.8	154.5%
Medium BWB subst narrowbody [Scaled off Boeing/NASA Large BWB]												
		135%		39.8%	63.2	181	1151	0.65		1,776	117.0	85.1%
Small BWB subst Regional Jets [Scaled off Boeing/NASA Large BWB]												
		135%		39.8%	41.7	78	576	0.99		582	77.2	85.1%
Weighted average												
Harmonic weighted by active aircraft vs. no techn.				41.7%	59.3						103.6	74.9%
Harmonic weighted by active aircraft vs. AEO 2004				35.1%								64.9%
System Savings (ATM & Load Factor)												
ATM-related savings (block fuel savings) vs. AEO 2004			11.0%	42.2%								
Load factor improvement (block fuel savings) vs AEO 2004			5.1%	45.2%								
Fuel savings, total stock (Quads)				2.25								

Table 12-4 Summary of *State of the Art* technology portfolio.

A Blended-Wing-Body aircraft has an inherent configuration benefit over the traditional tube-and-wing shape; see Figure 2 below. Comparing a 468-seat BWB (model *450-1L*) to a 420-seat Boeing *747-400*, the configuration effect gives a 20% reduction in block fuel[i] use [16, Fig. 1.10, p. 9] before adjusting for the seat difference. Accounting for the difference in seats, this translates to a ‘seat-adjusted’ 39.3% improvement in terms of seat-miles per gallon. A range of 10–19% on a per seat-mile basis is given in [11, p. 10], but due to lack of clarity around the baseline and comparison seat configurations in this reference, we cite the definitive block fuel reductions found in the Boeing/NASA literature.

---

[i] Units of “block fuel use” are lb fuel use per lb payload per defined distance flown, including a pre-set characteristic departure-to-arrival gate pattern consisting of departure taxiing, takeoff, cruise time and speed, approach and landing, and taxiing to arrival gate. Assuming a constant payload per seat, a percentage block fuel use reduction is similar in nature to a fuel-efficiency gpm measure and is therefore subject to the standard method of converting to the fuel economy measure SMPG, where differences in seat-numbers per aircraft have to be adjusted for.

Within the 2010 timeframe we apply the above *Conventional Wisdom* UEET engine technology, using the scaling methodology in the previous section to translate this and further savings from the widebody class to the narrowbody and regional segments. Improved Propulsion-Airframe Integration would partially or fully bury the powerplants within the fuselage, the latter giving a fully embedded wing propulsion (EWP) engine configuration. EWP has the standard and inherent challenge of the fuselage air boundary layer being nonuniform, thus exposing the engine fan to nonuniform and erratic pressure and velocity gradients, potentially resulting in erratic momentum thrust, i.e. unpredictable performance and incremental fuselage wear.

Boundary layer ingestion (BLI) engine inlets with active flow control (AFC) solve this issue [16] via use of pulsating air jets for boundary-layer control (requiring lower secondary flow rates than with continuous flow). This permits the mounting of the engines within the aft part of the fuselage and gives reductions in ram drag from BLI. Weight and drag benefits also result from elimination of engine pylons, reduced nacelle exposed surface area, and elimination of any potential engine/wing interference drag issues.

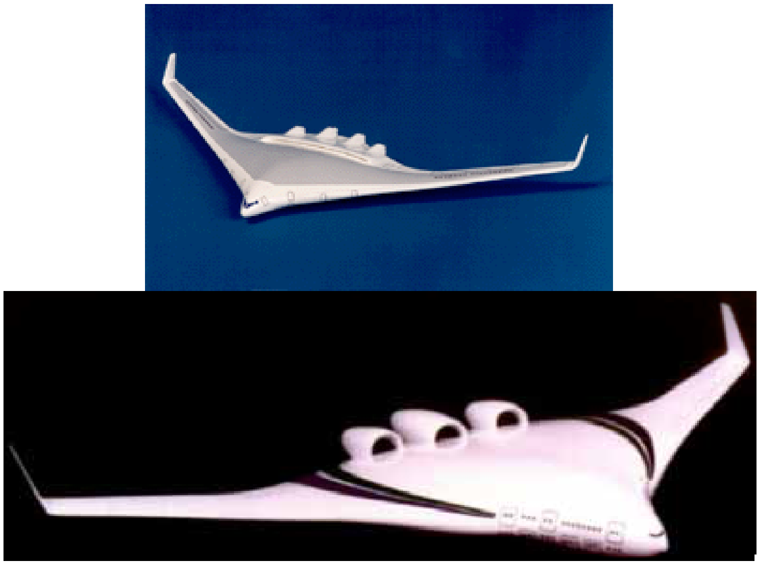

Figure 2: Typical Propulsion Blended-Wing-Body aircraft concept, here shown with a small number of large engines and with design payload 800 passengers. Sources: http://www-psao.grc.nasa.gov/ (top); [10, p. 3] (bottom).

Fuel use reductions from aircraft-specific technologies: Using **UEET engines** and **an improved airframe** for both these aircraft types gives a block fuel reduction of 30.6% for the *747-400* and 39.2% reduction for the BWB (model *450-1U*) versus a baseline 2000 vintage *747-400*. This translates to a 44.1% increase in SMPG for the improved *747-400*, and an 83.3% increase in SMPG for the BWB *450-1U*, with the large latter increase due to carrying more seats for less total fuel. While the BWB *450-1U* achieves a 24% block fuel reduction versus a baseline consisting of the *450-1L* from addition of

UEET engines and aerodynamic refinements [16, p. 8], the *450-1U* still suffers from an incomplete Propulsion-Airframe Integration (PAI) in that the engines are pylon-mounted (placed in freestream air thus completely separated from the body), rendering further gains possible.

Boeing/NASA modeling results [16] conclude that achievable fuel efficiency benefits from **wing-embedded engines** would be 6.3% from ram drag reduction alone when compared to a conventional pylon-mounted engine, or 5.5% when including engine performance losses and net drag and weight effects from resizing and PAI benefits from thrust reverser integration vs. baseline pylon engine mount. This assumes that **active flow control** (AFC) achieves insignificant inlet distortion levels and requires negligible power to drive the system. On the other hand, without adequate AFC, a longer, narrower diffuser with less **boundary layer ingestion** (BLI) and passive airflow control devices would be required and the maximum airplane performance benefit would only be 0.4% versus the *450-1U*. We assume that AFC inlet distortion and power requirements are negligible in the *State of the Art* portfolio, for a 5.5% gain in fuel efficiency.

These analyses were based on changes to the nacelle and pylon only, and did not evaluate the **integrated overall effect on airplane aerodynamic performance**. Such an analysis is expected to show improvement in overall streamlining, for a total net benefit larger than 5.5%. The fuel efficiency benefit that a BWB *450-1U* with BLI and AFC would achieve is therefore conservatively 42.5% versus a traditional *747-400*. This equates to an 11.9% improvement over a *747-400* comparably outfitted with UEET Propulsion-Airframe Integration. Further improvements that may increase the fuel burn benefit beyond 5.5% also include **canting the leading nacelle edge** as well as **moving it forward**, together with **moving the engine forward and further down**, and **reduced flow turning within the air pathway**. These would result in further wetted surface area reduction, reduced back pressure on wing shocks, reduced engine support moments, and reduced lower diffuser adverse pressure gradients. **Buried engine installations** with BLI intakes would also greatly reduce frontal and cross sectional areas, an additional military benefit [16, pp. 23–24, and Figs. 5.2 and 5.3, p. 24]. We have not accounted for these potential gains due to lack of good information on potential effects.

These figures also exclude potential benefits from **distributed propulsion**, [10], [11], [25], of which improved fuel efficiency is one[ii]. Under the assumption of a 25%

[ii] A number of small engines instead of a few large ones reduce the total propulsion system noise, partly because smaller engines produce a higher frequency range noise, which is more easily absorbed by materials and dissipates faster. A distributed propulsion concept may be employed as a seamless high-lift system, eliminating conventional high-lift systems that are major sources of airframe noise. Engine redundancy also improves safety: with numerous engines, an engine out-condition is not as critical to the aircraft's available thrust and controllability. Load redistribution provided by engines also has the potential to alleviate gust load/flutter problems, while providing passive load alleviation resulting in a lower wing weight. There is also the possible improvement in affordability due to the use of small, easily interchangeable engines. Aerodynamic benefits of distributed propulsion also result if there is a synergistic integration between the propulsion system and aircraft airframe. The idea of an integrated propulsion/lift system is already evident in nature, where animals in flight generate lift and thrust using the same organs

achievable propulsive wake-fill efficiency capture relative to the theoretically possible capture, an incremental 4.5% TOGW reduction and 2.3% airplane fuel weight reduction [11, Table 6.5, p. 122, p. 126] will result from flying the same 800-passenger load at 0.85 cruise Mach number and 7,000 nmi range mission with a distributed propulsion BWB aircraft (8 engines) versus a normal 4-engine BWB aircraft. While [25] considers two additional configurations involving 14 and 264 engines, fuel efficiency gains in that study were concluded to be positive, but were only addressed qualitatively. It is worth noting that while not a practically attainable figure, the theoretically possible (100%) capture would reduce the normal BWB TOGW by 5.7% and engine specific fuel consumption (SFC) by 13.9% [11, Fig. 6-12, p. 135]. The cited study concluded that even if only 10% of the maximum possible savings in propulsive efficiency could be obtained, a 1.4% decrease in engine SFC would result—a significant improvement in light of currently mature engine technology [11, p. 147].

The analysis suggests nominal reductions of 5.4% TOGW and 7.8% engine SFC as a value for the optimization results [10, p. 17] distributed over *Conventional Wisdom* propulsion, primarily achieved by increased propulsive efficiency from “filling the wake,” lower trailing edge induced drag, and elimination of traditional elevons (flaps). However, as the aircraft configuration studied in [10] and [11] is larger than that considered in [15] and [16], and as there is some lack of clarity around how close the engines in [10] and [11] are to UEET, we have assumed that one half of the nominal gain, or 3.9%, is mission fuel weight reduction that can be transferred to what in this study is the comparison, the smaller BWB *450-1U* with BLI and AFC. This distributed propulsion BWB’s block fuel burn would therefore be a 44.8% block fuel improvement versus a 2000-vintage traditional *747-400*, i.e., a 14.2% improvement over a *747-400* comparably outfitted with UEET Propulsion-Airframe Integration.

As noted above, the advanced airframe technologies just described above deploy lightweight materials that have been found likely to be technology-ready by 2010 (for an entry-into-service date 2015). These technologies and materials were deployed in the “fuselage, wings, engine nacelles, empennage, and canards to reduce the weight of the aircraft and thereby reduce the amount of takeoff thrust and generated lift required” [14]. Further deployment of lightweight carbon-based composite materials throughout the fuselage would seem likely within the timeframe of this study, perhaps incorporating some of the conservatisms listed above and likely to the level noted in [20].

In parallel with the developments described in the section on light automobile passenger vehicles, we would therefore expect to find the Operational Empty Weight (OEW) of an aircraft built in 2025 to have a further reduction in OEW of approximately 10%, or a reduction in TOGW of about 4% in the *State of the Art* case. We estimate the impact of this TOGW reduction via the elasticity of en route fuel reduction with respect to weight. Using the aircraft-type takeoff gross weights (TOGW) in Tables 3-2 and 3-3 in [26, p. 12 and 14] and the estimates of incremental fuel consumption (in gal/airborne hour/500 lb), the elasticity of en route fuel reduction with respect to weight ranges from 0.816 for a *737-300* to 0.973 (*747-400*), 1.07 (*DC-10*), to 1.28 (*767-332ER*). Any generic Propulsion-Airframe Integrated design with a 4% TOGW mass reduction therefore roughly translates into a 4% reduction in en route transport fuel, or somewhat less for block fuel use. Applying 0.75 as the elasticity of block fuel reduction with respect to weight for near-optimized aircraft, a BWB *450-1U* with BLI, AFC, and DEWP would get a 3% block fuel use reduction prior to applying the 20.7% improvement from a 2010 to a 2025 vintage. While application of further lightweighting is plausible, and indeed the Skunk Works fighter design mentioned above offers a particularly promising method for very substantial weight and cost reductions in a civilian BWB design, as a conservatism we choose to incorporate the 3% block fuel use reduction in this 20.7% improvement. In sum, this results in a block fuel use reduction of 56.2% vs. a 2000 vintage *747-400*. This translates to a 14.5% improvement over a comparably outfitted 2025-vintage average widebody aircraft. Based only on improved aircraft design this gives a technically achievable 2025 saving of approximately 35.1% vs. *AEO04* 2025.

Regarding **hydrogen-powered aircraft**, it has been found that for short-range missions (<3,000 nmi), the performance or weight of a LH_2 turbofan aircraft is similar to that of a kerosene-fueled design, largely due to the aerodynamic penalty outweighing the smaller weight reductions for this operational range, thereby providing no significant advantages. The main advantage appears to occur for long-range missions (5,000+ nmi), where LH_2 aircraft design, with some use of lightweight materials and integrated design, could result in a 40% reduction in TOGW, and a 71% decrease in fuel weight, vs. today's aircraft. The LH_2 aircraft therefore requires a smaller wing area, and shorter span. The main disadvantage of this aircraft is its greater aerodynamic drag from its longer and larger fuselage [11, pp. 177–178].

Earlier studies have done extensive research into design of hydrogen-fuelled engines, pumping and insulation subsystems, and ground refueling options [27]. These technologies are certainly going to be necessary if aircraft-related emissions are to be reduced significantly [28]. Pressurization and insulation of the LH_2 fuel tanks and systems would be challenging in the BWB configuration due to the non-tubular aircraft hull and a high surface area to volume ratio [11, pp. 177–178], although high-altitude, long-endurance aircraft for the U.S. Air Force using hydrogen fuel have been designed [29] with fuel stored in the wing sections. This is what would be required in the BWB aircraft, and several fuel tank options were presented including integral and non-integral pressure tanks. [11, p. 178] concludes that, based on research already done, designing the BWB aircraft to use hydrogen fuel should therefore be a straightforward problem—as far as this analysis is concerned, the issue around deployment appears to be timing.

Fuel use reductions from ATM and load factor operational gains: Again, savings potential and costs are difficult—at best—to estimate from ATM-related technologies, and again, we have left the ATM discussion as a separate topic towards the end of this section due to the technical similarity between the two portfolios. While we relied on Eurocontrol and FAA estimates for *Conventional Wisdom* technologies for improving ATM, for a 5.1% saving of fuel incremental to EIA *AEO04*, for *State of the Art* we choose the average of the high and low of the four estimates (see section below), or 11%, since this appears technically feasible and has some plausible probability of occurring.

Costs are again very difficult to estimate, so we have assigned these at an average cost approximately equal to the portion of all non-ATM *State of the Art* technologies.

While according to [22] load factors of 0.9 are feasible through advanced bookings and use of an optimal size of aircraft, we use a load factor growth of 0.25% in the *State of the Art* portfolio. This gives 80.3% load factor, respectively, or a 5.1% drop in seat-miles demanded.

Summary of energy saved and costs of savings: For the *State of the Art* technology portfolio we assume that there will be migration from the tube-and-wing to the Blended-Wing-Body aircraft shape and, again, that one of several possible small discontinuities will actually occur, as discussed in the *Conventional Wisdom* technology section. However, because we expect *State of the Art* technologies to be somewhat more expensive than *Conventional Wisdom* technologies, we have used 0.30–0.35% as a more likely annual growth of per-unit commercial aircraft costs 2000–25 with *State of the Art* technologies. We again base our cost estimates for fuel savings potential on historical cost developments as well as estimates from the literature on expected future cost developments, as described above, with real operating costs expected to drop by another 45–60% in the years to 2025–30 [7, Figure 6.6, p. 125, 1995$].

We find a 2025 block fuel use reduction of 45.2% vs. *AEO04* 2025 baseline, representing 2.25 quads of saved fuel. Scaled to the commercial fleet, this becomes 10.2b gallons, or between 758,000 and 871,000 gallons per average 2025 aircraft-year, with the higher figure arising from a reduction in total aircraft demand as a result of greater seat-capacity in BWB aircraft. At the 25-year expected life, the annual capital recovery factor at 5%/y real discount rate is 7.10% of the upfront capital cost, leaving the annualized capital cost between $0.40M and $0.46M before accounting for portions of the investment not related efficiency.

For this portfolio we assign a more conservative 25% of the real incremental cost as non-efficiency related investment. This leaves the annual cost of per-unit efficiency at between $0.30M and $0.35M. This implies a cost of the saved fuel of between $0.39/gal and $0.46/gal jet fuel, or between $9.06 and $11.97 per barrel of crude after energy- and value-chain adjustments.

Air Traffic Management (ATM) and other load-factor related technologies

While Air Traffic Control operations could reduce fuel burn from aircraft operations in several ways (discussed in more detail immediately below), it is not clear to what extent fuel savings would actually materialize from technology implementation. Broadly speaking, the net effect depends on the degree to which ATM-related technologies relieve congestion versus their use to expand system capacity. Due to major uncertainties around actual impacts we have used the Eurocontrol and FAA expected effect for our *Conventional Wisdom* technology portfolio, 5% off a given baseline. For *State of the Art* we have use the average high range savings from four separate estimates, or 15%. Technology costs are very difficult to estimate. We know these are greater than zero, yet they are in all likelihood not necessarily very high. We have therefore chosen to assign to ATM-related measures the average Cost of Saved Energy related to non-ATM measures for the given technology portfolio.

While several systems implicitly reduce congestion, their design-purpose is commonly to improve capacity. Major improvements beyond the continuous level of improvement that is occurring would be required in aircraft ground, takeoff, and landing operations to move the ratio of airborne hours to block hours up from its quite constant historical average of 0.85 [7]. If ATM improvements stay at current levels, the same also holds true for the flight time efficiency, which measures minimum flight hours to airborne hours. It has remained consistently at 0.85 with these improvements. Therefore, unless major airport capacity increase or significant avionics technology improvement occurs in the near term, total flight time efficiency is expected to remain at the current level of 0.72 [7]. The bulk of the reason for this is rapidly growing aircraft fleet sizes congesting airport alleys and runways, in turn offsetting ATM improvements to the point where even significant airport and ATM improvements may merely hold airport delays constant in the future.

On a simple average basis, researchers have found that improvements in ATM infrastructure could theoretically reduce fuel burn per trip by between 8% and 15%; on average 11%. Some find 6% to 12% on average [30]. Improvements in aircraft utilization, optimal cruise speed, operational weight and improved taxiing could lead to further potential reductions in fuel burn per trip of 2–6% [30]. Studies on military system efficiencies suggest similar possible gains [20], with wind optimization giving a 2.8% fuel reduction and a 2.3% time-reduction, 2–3% fuel efficiency from better communications, 1–2% from near-real-time global flight planning, and 7+% from in-flight rerouting/rescheduling. The same source cites civilian traffic gains of 6–17% from full CNS/ATM (Communications, Navigation, Surveillance/Air Traffic Management). Others find similar results: total improvements in ATM and other operational improvements could reduce fuel use by 8–18% [31]. However, while up to 12% of this has been expected to come from full global implementation of ATM improvements by 2017, the rate of improvement will depend on the implementation of essential institutional arrangements at the international level. As such, current collaborative work between Eurocontrol and the U.S. FAA predicts that currently anticipated ATM enhancements would only provide a saving of 5% by 2015—much lower than projected [31].

ATM technologies focused on ground-level operations: Some of the ATM-related technologies around the airport terminal include Advanced Surface Movement and Guidance Control Systems (A-SMGCS) and related ground-management systems. These could reduce onground engine run-times, include tow-to-takeoff, and reduce thrust settings during pre-takeoff and landing by achieving fuel-optimal ascent and descent using Advanced Continuous Approaches. Surface Management Systems mainly improve the efficiency of surface movements by reducing taxiing times by addressing scheduling and routing of aircraft and other airport vehicles that could influence aircraft movements. The system operates between the gate and the runway, and can be considered as the routing and planning functions of A-SMGCS. To date, these systems are only concepts and their implementation timeframe is long-term [30]. They are most applicable to major airports with high volumes of traffic and complex taxiways and maneuvering area layout implying many alternatives for routing, and can improve airport capacity, especially in low visibility conditions, by providing situation awareness to the controller and to other proximate aircraft and vehicles.

Implementation of an Arrivals Manager could bring an improvement of up to 20% in aircraft separations [30], and hence capacity increases, via optimizing traffic flow in and around the Terminal Maneuvering Area (TMA), decreasing average congestion periods, increasing runway rate, and decreasing holding patterns. Such systems are at the prototype stage with just a few basic systems starting to be deployed, for example at Frankfurt airport [30]. Departure Management Systems (DMS) are ground-based air traffic management automation tools for approach and area controllers designed to optimize traffic flows in and around the TMA. A DMS generates advisories for the controller in order to meet the planned departure sequence, thus optimizing the metering and sequencing (i.e. spacing and ordering) of the outbound traffic. The Automatic Slot Assignment system has been developed and is installed at Schiphol [30]. A natural progression albeit long-term prospect in the development of Arrivals and Departure Managers would be system integration to smooth flow of traffic into and out of the TMA. Use of chip (or smart) cards and Radio Frequency (RF) tags for passenger and baggage ID is expected to further lower congestion, with industry estimates at a 50–80% reduction in check-in and handling time [30].

ATM technologies focused on airspace operations: On-board Global Positioning Systems (GPS) and modern Flight Management Systems (FMS) could enable Direct Routing, whereby the aircraft determines an optimal flight path from start to destination airports without reference to fixed points on the ground—known as point-to-point free flight. Satellite Landing Systems could offer an alternative new technology for Category I landings at busy and small airports, using information transmitted by either GPS or Global Navigation Satellite Systems (GLONASS), or both. For landing systems, the guidance information is calculated on board the aircraft and is based on the aircraft's current position and the coordinates of the runway. At busy airports with frequency allocation limitations or the potential for interference of the unprotected Instrument Landing System (ILS) signal, these systems may offer an alternative to ILS.

The introduction of technologies to address wake-vortex effects could improve runway/terminal airport capacity through reduced aircraft separations, e.g., via technologies that track vortices and predict their occurrence. This would allow controllers to optimize in real time the spacing between aircraft based on a real understanding of the vortices generated and their dispersal, possibly resulting in reduced aircraft spacing and hence increased movement density. Boeing’s wing-tip wake vortex cancellation technology causes vortices to collide with each other a short distance behind the aircraft, resulting in quicker dissipation [31].

For the EU three concept options exist for the future airspace structure: Structured Routes (Flexible Use of Airspace (FUA), flight along a fixed set of routes), Free Routing (allows users to plan route without reference to the Air Traffic Service (ATS) route network in place today), and Free Flight and Autonomous Operations (allows a suitably equipped aircraft to fly user-preferred trajectories). Simulations suggest that the Direct/Free Routing concept can provide a 17–40% gain in en route capacity [30]. This concept depends upon the implementation of new technologies such as air-ground datalinks, redundant Global Positioning Systems, sophisticated Flight Management Systems, and advanced automation tools.

Conservatisms—technologies that have not been included

We have left out several technological developments for a variety of reasons, mostly having to do with the great degree of difficulty in assessing potential impact and costs, or with compromising on airspeed. A selection of these is briefly summarized here.

We have as a major conservatism excluded wide application of efficient **high-speed propeller propulsion** (turboprop) travel, and we did this because wide application of this efficient technology would involve lowered design air-travel speed. But it is obviously well worth noting that an aircraft using high-speed propellers and traveling only some 15% slower than a comparative jet aircraft would use about 50% less fuel [1, p. 1], and probably do so at a *lower* capital cost. We exclude this option as it entails a 1–2 hour increased transoceanic journey length, an increase that might not be considered to provide a comparable level of service to that of a jet aircraft. However, on short missions, where airspeed is less important and is diluted by ground stages, this technology could be quite attractive, and in concert with improved ground and landside operations, there could be an especially large benefit in fuel savings for commuter and regional fleets. We have included some turboprop examples in Fig. 25 of our main narrative report, however, to illustrate their potential to exceed the aggregated ~35% airplane efficiency gains in the regional-aircraft component of our *State of the Art* scenario.

We have also excluded **pneumatic blowing**. This option would probably have major fuel reduction consequences, see [32] and [33, Fig. 2], although we have found it difficult to determine how big or at what cost in energy-input and monetary terms. Because the very low required blowing input and associated power required to achieve a desired lift, it has been noted that the “[c]irculation Control airfoils appear very promising for a number of applications. …The A-6/CC Wing Short Take Off & Landing (STOL) flight demonstrator aircraft showed … during short takeoff, … high lift with reduced drag” [33, p. 2]. Indeed, in that experiment, the coefficient of lift was increased by 140%, reducing takeoff and approach flight speeds by 30–35% and associated ground rolls by 60–65% while increasing liftable takeoff payload by an astonishing 75%. We assume that, like turboprops, pneumatic blowing would probably be most attractive for short hauls, where aircraft efficiencies are also currently the lowest.

For all aircraft, we make no explicit allowance for more efficient **electric end-use and generation** onboard. Optimized (even fuel-cell) auxiliary power units can probably outperform current engine-linked generators, and electric end-use efficiency has not yet received the comprehensive and systematic attention warranted by its potentially important benefits for airplane empty weight and fuel weight (both compounded) as well as for fuel cost. We estimate that the overall benefit might be on the order of a 1% fuel saving for a modern midsize aircraft, with very attractive economics, but this could increase for new models that substitute electric for hydraulic actuators.

We also exclude **intelligent software agents** for advanced freight logistics. These are currently under development by the DARPA Advanced Logistics project, and apparently good progress has been made to date.

One additional area is a new breed of business aircraft, dubbed "**air limos**" or "**air taxis**." These are being developed to address direct trajectory efficiency gains. Analytically, the issue that is difficult to tackle is what fraction of the new breed will fly trips that displace journeys that otherwise would have required two flights. Moreover, given that each of the two flights would have been "produced" using larger aircraft with a better efficiency per seat-mile, there is no doubt a net gain from direct routing, but we would have to make some assumptions that are in need of further documentation in order to make a quantification estimate. Accurate predictions of load factors and aircraft relative efficiencies are additional difficulties. While we incline more toward the sanguine view of the air-taxi concept's NASA sponsors than of its NAS/NRC skeptics, and agree that commercial success of both the airplanes and the operational business model could greatly reduce both aircraft movements and aircraft miles while saving customers much air and ground time and hassle, there is simply too little known yet to analyze the implications credibly.

For completeness, however, it is worth noting that such manufacturers as Adam Aircraft Industries Inc., Cessna Aircraft Co., and Eclipse Aviation Corp. (plus Cirrus, Sapphire, etc.) have announced four-seat-cabin jets designed to ferry business travelers on point-to-point routes. Initial pricing is expected to be around $3–4 per mile, which is just above most first-class tickets [34]. The mini-jets are expected to enter the market in 2006. The aircraft will cost between $1 million and $3 million, and one source claims costs of less than 75 cents a mile [35]. Williams International is powering the Adams Jet. Two leading automakers—synonymous with lean manufacturing—and their heavyweight industrial counterparties are also exploring the possibility of entering the aerospace market. With General Electric Co., Honda Motor Co. is working on a small, twin-engine jet that preliminary tests indicate will have a 40% decreased bulk fuel use relative to comparable existing planes. Toyota Motor Co. has developed a four-seat propeller-driven prototype. Also, Pratt & Whitney, part of United Technologies Corp., is testing a new engine that will power the Eclipse Jet. Eclipse Aviation claims the six-person, twin-engine Eclipse 500 will cost "approximately a quarter of today's small jet aircraft and will be significantly safer, easier and less expensive to fly, enabling the creation of new forms of air travel that will provide much-needed alternatives to the commercial airlines" [35]. As much as one-third of these gains are expected to come from improved friction stir welding technology that will replace rivets, the rest from automated lean manufacturing and whole-systems design.

Excluded are also **better-optimized modal splits**, **local production to avoid air transport**, and policies focused on **aviation emissions**, **taxes**, **ticket VAT**, and **de-subsidization**. These all represent possible options which are unlikely to appear either for political, logistical, or other reasons such as being disadvantaged due to factors not having to do with transportation (e.g., climate).

Finally, we exclude **solutions-economy business models** (as described in *Natural Capitalism*, Chapter 7, www.natcap.org), which in this context would lease an access or mobility service rather than selling airplanes or gallons. This approach is potentially very powerful because it aligns provider- with customer-interests, and is being examined by many car and oil companies as a possible alternative to selling and fueling light vehicles. The likely commercialization in this decade of attractive virtual-reality technologies over superbroadband (Internet2) could make solutions-economy models for commercial aviation even more interesting because physical and virtual mobility could be seamlessly integrated according to a customer's needs for each trip or "negatrip."

REFERENCES

---

1 J.M.W. Dings, P.M. Peeters, J.R. van der Heijden, and R.A.A. Wijnen, "ESCAPE: Economic Screening of Aircraft Preventing Emissions," Delft, CE, Solutions for environment, economy and technology, August 2000. Both Main Report and Background Report are available at: http://www.cedelft.nl/eng/publicaties/00_4404_16e.html

2 Daggett, D.L., "Commercial Airplanes: Hydrogen Fueled Airplanes," Boeing presentation at *Hydrogen Production and NW Transportation*, Seattle, WA, 16 June 2003. Available online at www.pnl.gov/energy/hydrogen/presentations/daggett.pdf.

3 D. Daggett, personal communication, 16 June 2003

4 H. Quack, "Conceptual Design of a High Efficiency Large Capacity Hydrogen Liquefier," undated, Technische Universität Dresden, 9 pp. To get from 5 to 4 kWh/kg, the senior author of this study has applied estimates, based on his LNG experience, for adding to Quack's design close-approach heat exchangers, absorption (to about –40˚C) and possibly evaporative or desiccant/evaporative precooling to reduce chiller lift, and efficient auxiliaries. Thermoacoustic refrigeration may offer an alternative route.

5 P. Peeters, section 1 in *ESCAPE (Economic Screening of Aircraft Preventing Emissions, Annex I: Designing aircraft for low emissions; technical basis for an ESCAPE project*, 2000, www.ce.nl/eng/publicaties/00_4404_16e-d2.html, (This Annex is the same as the Background Report in ref. 1 above.) Peeters Advies (Rodestein 12, NL-6714 CG Ede, The Netherlands).

6 C. Snyder (NASA), "Zero-Emissions Aircraft?," NASA Environmental Compatibility Research Workshop III, Monderey CA, 7 July 1998.

---

7 J. J. Lee, "Historical and Future Tends in Aircraft Performance, Cost, and Emissions," M.Sc. in Aeronautics and Astronautics, University of Illinois at Urbana-Champaign, and M.Sc. in Technology and Policy, MIT, Sept. 2000. Available online at www.mit.edu/people/jjlee/docs/lee_thesis.pdf

8 H. Smith et. al., "Blended Wing Body Preliminary Design Study," Cranfield College of Aeronautics, 1999, see http://www.cranfield.ac.uk/coa/tech-avt/wing/wing-8.htm

9 Boeing prices listed on http://www.boeing.com/commercial/prices/, Airbus listed on http://www.airliners.net/discussions/general_aviation/read.main/1464844/

10 Andy Ko, Leifur T. Leifsson, W.H. Mason, J.A. Schetz, Bernard Grossman, and R.T. Haftka, "MDO of a Blended-Wing-Body Transport Aircraft with Distributed Propulsion", Virginia Tech, U. of Florida, and NASA, presented at AIAA 3rdAnnual ATIO Technical Forum, Denver November 17, 2003. Available at www.aoe.vt.edu/research/groups/bwb/presentations/ATIO-Nov03.pdf

11 Yan-Yee Andy Ko, "The Multidisciplinary Design Optimization of a Distributed Propulsion Blended-Wing-Body Aircraft," Ph.D. Dissertation, Virginia Institute of Technology, April 2003. Available at: http://www.aoe.vt.edu/~mason/Mason/ACiADblended.html

12 G. Polek, "Boeing Seeking Ways to Make the 7E7 Work," AINonline, June 2003, at http://www.ainonline.com/Publications/paris/paris_03/pd1boeingpg40.html

13 David L. Daggett, Stephen T. Brown, and Ron T. Kawai, "Ultra-Efficient Engine Diameter Study", NASA CR-2003-212309 (or NASA CR 2003-C03-003), May 2003. Available at http://gltrs.grc.nasa.gov/cgi-bin/GLTRS/browse.pl?2003/CR-2003-212309.html

14 Daggett, D.L., "Ultra-Efficient Engine Technology Systems Integration and Environmental Assessment," NASA/CR—2002-211754, July 2002. Available from http://arc.cs.odu.edu:8080/dp9/getrecord/oai_dc/ltrs.larc.nasa.gov/oai:ltrs.larc.nasa.gov:NASA-2002-cr211754; or directly at: http://techreports.larc.nasa.gov/ltrs/PDF/2002/cr/NASA-2002-cr211754.pdf

15 Daggett, D., Kawai, R. and Schuster, E., "Blended Wing Body Systems Studies," UEET Task 33, December 2001

16 David L. Daggett, Ron Kawai, and Doug Friedman, "Blended Wing Body Systems Studies: Boundary Layer Ingestion Inlets With Active Flow Control", The Boeing Commercial Airplane Group, Seattle, Washington, NASA/CR-2003-212670, December 2003. Available online at http://www.techreports.larc.nasa.gov/ltrs/PDF/2003/cr/NASA-2003-cr212670.pdf

---

17 F. Kocian & W. Dudenhausen, (DLR Stuttgart) “Aeroengines—Conservative Design Contra Fiber Reinforced Materials?,” in K. Drechsler, ed., *Material & Process Technology—The Driver for Tomorrow's Improved Performance*, Proc., Society for Advanced Materials and Process Engineering (SAMPE), Europe 25th Jubilee Intl. Conf., Paris, 30 Mar–1 Apr 2004, SAMPE Europe, Aalsmeer, NL, pp. 147–152

18 M. Kupke & M. Kolax (Airbus), “CFRP-Fuselage-Ensuring Future Competitiveness,” in K. Drechsler, Ed., *Material & Process Technology—The Driver for Tomorrow's Improved Performance*, Proc., Society for Advanced Materials and Process Engineering (SAMPE), Europe 25th Jubilee Intl. Conf., Paris, 30 Mar - 1 Apr 2004, SAMPE Europe, Aalsmeer, NL, pp. 432–437

19 Taggart, D.F., “Advanced Ultralight Airframe Design,” brief to The Defense Science Board Task Force on *Improving fuel efficiency of weapons platforms: More capable warfighting through reduced fuel burden*, January 2001.

20 Defense Science Board, Task Force on Improving fuel efficiency of weapons platforms: *More capable warfighting through reduced fuel burden*, January 2001, p. 63. Available online at www.acq.osd.mil/dsb/fuel.pdf

21 “Japan order launches Dreamliner,” BBC News, 26 April 2004. Available online at http://news.bbc.co.uk/2/hi/business/3659451.stm

22 Barret, M., “Aircraft Pollution: Environmental Impacts and Future Solutions,” WWF Research Paper, August 1994 [cited from Lee, J.]

23 Airbus, “Global Market Forecast”, p. 17, November 2003. Available online at http://www.airbus.com/media/gmf.asp

24 David H. Napier, “2003 Year-End Review and 2004 Forecast—An Analysis,” Aerospace Research Center, Aerospace Research Association, 2004. Available online at www.aia-aerospace.org/stats/yr_ender/yrendr2003_text.pdf

25 Hyun D. Kim and John D. Saunders, “Embedded Wing Propulsion Conceptual Study,” NASA and Glenn Research Center, prepared for Vehicle Propulsion Integration Symposium, NATO Research and Technology Agency, Warsaw, Poland, October 6–9, 2003, published as NASA/TM 2003-212696, November 2003. Available online at http://www.techreports.larc.nasa.gov/ltrs/PDF/2003/cr/NASA-2003-cr212670.pdf

26 “Impact of Weight Changes on Aircraft Fuel Consumption,” Federal Aviation Administration (FAA), July 1998. Online at http://apo.faa.gov/arcc/Research.htm

27 Brewer, G.D., “Hydrogen Aircraft Technology,” CRC Press, Boca Raton, Fl., 1991

---

28 Paul Peeters and Jos Dings, “Climate change, tourism and air transport: Globally sustainable tourism requires clean air transport,” NHTV-CSTT, Breda, The Netherlands, November 2003. Available online at: www.icis.unimaas.nl/workshop/nato/downs/peeters_dings.pdf

29 Brewer, G.D., “Configuration Integration for High Altitude Aircraft,” AFWAL-TR86-3063, Vol. 2, Lockheed-California Company, Burbank, January 1987

30 Liz Orme, “The role of future technology for aviation and the environment,” Arthur D. Little White Paper, The Ashden Trust's Aviation and Environment Seminar, Heathrow Airport, 1-2 March 2001

31 Dave Lester, “Aviation and Climate Change,” Defence Evaluation & Research Agency, UK, Jan.–Feb. 2001

32 Robert J. Englar, et al., “Design of the Circulation Control Wing STOL Demonstrator Aircraft,” AIAA 79-1842, August 1979

33 Robert J. Englar, “Drag Reduction, Safety Enhancement, and Performance Improvement for Heavy Vehicles and SUVs Using Advanced Pneumatic Aerodynamic Technology,” SAE Technical Paper Series, 2003-01-3378, November 2003

34 Scott McCartney, “Taxi! Fly Me To Cleveland,” *Wall Street Journal*, Wednesday 19 May 2004, p. D10

35 Austin Weber, “Aerospace Prepares to Soar Again: Today's gloom will evolve into tomorrow's boom” *Assembly Magazine*, 9 June 2003. Available at http://www.assemblymag.com/CDA/ArticleInformation/coverstory/BNPCoverStoryItem/0,6490,101622,00.html