Auxetic Balancing Technology:
Investigation into the benefits of weight saving in the global aerospace market

Final Report
For
Global Composites Group

Dr Francesca Medda
Luca Cocconcelli
Qianwen Liu

UCL QASER Lab
University College London
Contents

1. Introduction ........................................................................................................ 3

2. Macro Trends in Air Passenger Transport .......................................................... 5

3. Economic Benefits of Reduced Weight ............................................................... 8
   Fuel consumption ................................................................................................. 10
   Maintenance ......................................................................................................... 16
   Other operating charges ...................................................................................... 17

4. Application to the Future Airline Fleet .............................................................. 20

5. Conclusions and Next Steps ............................................................................... 28
1. INTRODUCTION

Demand for air transportation has historically closely shadowed the rate of global GDP growth and so as economies continue to grow, traffic volumes increase and energy use rises. As heightened environmental awareness spreads from its ideological roots to becoming a policy priority for all industrialised nations and diminishing oil supplies puts increasing pressure on the economics of airline operators, new solutions must be sought to meet the burgeoning demand from passengers worldwide if low cost, mass air transportation is to remain a reality.

The complexity of modern air transportation involves the coordinated use of a great many flight procedures, aircraft components, regulatory steps and skilled professionals both in the air and on the ground. Efficiency improvements in this sophisticated chain have been numerous and widespread, led by technology manufacturers and system integrators as well as innovative airline operators pioneering new passenger handling methods. It is estimated\(^1\) that between 1960 and 2000 advances in aircraft efficiency (as measured by energy intensity per seat mile) have been achieved from:

- Improving engine fuel per unit thrust (69% of overall improvement)
- Aerodynamic improvements (27%)
- The remaining 5% was due to other factors, such as the scale effects of larger aircraft

Structural efficiency improvements (weight reduction) are believed to have made no contribution to improved energy efficiency over this period, as aircraft construction technology has remained largely static. However the latest generation of aircraft are increasingly featuring greater use of new aluminium alloys, titanium components and composite materials for secondary (non-load-bearing) structures.

Between 1971 and 1998 the fleet-average annual improvement in efficiency per available seat-kilometre was estimated at 2.4\(^2\). Future advances using incremental technology improvements will inevitably be slower as the current technology reaches maturity. With average annual passenger volume growth estimated at 4.7% per annum\(^3\) and inexorable long-term increases in fuel costs, it is clear that significant step changes in efficiency will be required to enable operators to continue to provide profitable expansion. Weight savings in aircraft are expected to form a significant source of efficiency improvement beyond 2010.

On the other hand, we observe how economies of learning in the aircraft industry have always shown a high rate in relation to other transport industries, that is, the learning rate for new technologies for new aircraft is 40%, thus the decision to implement a new technology must be analysed in great detail in order to justify prospective investments in terms of revenue flow.

Given this background, if we assume the possible introduction in the aviation industry of the auxetic balancing technology, our overarching aim is to understand the impacts of this new technology from a financial and economic perspective. Within this objective, this report aims to


\(^2\) Ibid.

\(^3\) Airbus, Global Market Forecast (2009)
develop a preliminary analysis of the economic effectiveness of the auxetic balancing technology. In particular, after having reviewed several of the key macro trends affecting development of the air transport industry, we assume that in a static analysis three primary cost areas are expected to be influenced by a reduction of aircraft weight:

(1) fuel consumption,
(2) maintenance and
(3) airport charges.

The objective of this study is to identify and quantify the cost savings achievable by operators of aircraft with reduced weight characteristics.

The likely penetration rate of aircraft featuring significant carbon fibre content is estimated, with their introduction put into the context of overall fleet size and growth. This allows for a preliminary conclusion to be drawn about the potential benefits of reduced-weight aircraft, consistent with the assumption that operating models and the allocation of costs remains broadly stable.

The work, given the type of data and the considered assumptions, represents an exploratory analysis into the impacts of auxetic balance technology in the airline industry, and therefore the results must be considered as preliminary. Additional, more stringent analysis is necessary in order to test the objectives and thus validate the examination undertaken here as well as to evaluate the robustness of the assumptions.
2. MACRO TRENDS IN AIR PASSENGER TRANSPORT

2.1 Air Passenger Growth

Global growth in air passenger demand is expected\(^4\) to occur at a compound rate of 4.5% p.a. from 2009-2018, accelerating to 4.8% p.a. in the period 2019-2028 as Eastern Europe, developing areas of the Asia Pacific region, and the Middle East and Africa gain in economic maturity.

![Evolution of World Passenger Demand by Region](image)

*Figure 1:* (Source: Airbus, 2009)

Meeting this overall growth in demand for passenger kms of 4.7% per annum will be achieved through a combination of increased service intensity and new aircraft. The migration to larger aircraft variants and increased service frequency are forecast to account for a 1.2% per annum increase in capacity\(^5\), however the balance will need to be found from an overall increase in the passenger aircraft fleet.

The current fleet of commercial aircraft with over 100 seats consists of around 14,000 planes, of which only 880 are expected to remain in service with their current operators by 2028 according to Airbus (2009) estimates. A further 3,100 will be recycled into continued use by second or subsequent operators, leaving a need for some 24,000 new aircraft to meet growth in passenger demand.

The continued prevalence of North America and Europe and emergence of Asia Pacific as key passenger volume centres is expected to ensure that increased demand is met from the latest

\(^4\) Airbus, Global Market Forecast (2009)

\(^5\) Ibid
aircraft types whose passenger appeal, operating cost and environmental performance meet the exacting standards set by consumers and governments in these regions.

2.2 Aviation Fuel Prices

Alongside higher end user demand, the air passenger industry is faced with the effects of rising oil prices. As can be seen below, the price of aviation fuel is highly correlated with crude oil prices, with additional adjustments imposed in some geographies for local taxation or currency management reasons.

![Historical Jet Fuel Price](image)

**Figure 2** (Source: US Energy Information Administration, 2009)

While no forecasts are available for fuel prices beyond those implied by the commodity forward markets which reach out some 3 months, the long-term trend in prices is undeniably upwards. The 2008 spike in oil prices and consequent effects on airlines’ profitability have served to underscore the importance of fuel-efficient aircraft with regard to airlines planning their next fleet upgrades.

We estimate that fuel consumption in the global aviation sector is rising at around 2.1% per annum\(^6\), with overall volumes running at c.220 million tonnes in 2010. At current European wholesale prices this equates to some $14.0bn spent annually on aviation fuel worldwide.

---

\(^6\)ICAO (2009) estimates. Consumption in 2006 estimated at 200-205 million tonnes, including fuel burn associated with aviation-related operations (e.g., auxiliary power units, ground support equipment, etc.), fuel burn by visual flight rules (VFR) flights and non-scheduled flights in regions for which radar data are not available.
2.3 Environmental Legislation

The Kyoto Treaty, signed in 1997, and which entered into force in 2005, imposed on signee governments a range of caps on CO$_2$ emissions across industrial, energy, agriculture, and domestic transport sectors amongst others. It has also prompted the development of carbon trading markets where corporates with highly efficient plants can trade unused carbon credits with those whose environmental performance has been slower to react. Liquidity on this market has grown to the point that a ‘market price’ of carbon dioxide production is now transparent, although prices remain subject to substantial volatility in response to new inter-government agreements.

However, international air and shipping transport has thus far been exempt from the Kyoto Treaty on reducing greenhouse gas emissions. This appears likely to change following the Copenhagen conference in December 2009, although recent moves by the US and China to dilute the content of any accord suggest it will be 2010 before substantive progress is made on new emissions targets.

At the International Air Transport Association (IATA)'s annual general meeting in 2007, a vision was laid out for the industry – to achieve carbon-neutral growth in the mid-term and to build a zero emission commercial aircraft within the next 50 years. This would be achieved through IATA's four-pillar strategy to reduce emissions: investment in technology; effective operations; efficient infrastructure; and positive economic instruments.

At IATA’s annual general meeting in June 2009, ambitious targets for emissions reduction were agreed; to stop the growth of emissions from 2020 and to halve emissions by 2050 compared to 2005 levels.

In September 2009, however, IATA presented proposals to the UN that would commit the industry to halving emissions from the sector by 2050, improving fuel efficiency by 1.5% annually to 2020, and ensuring emissions peak from the same date. The UN’s ICAO welcomed the industry's commitment to tackling emissions, but recommended that fuel efficiency should be improved by 2% annually to 2020 rather than 1.5%.

Negotiations on the final legal binding targets to be adopted by the ICAO as part of any international climate change deal agreed at the Copenhagen Summit later this year will not now continue. Giovanni Bisignani, IATA Chief Executive, later stated that “The challenge is to work together to close this gap by the next ICAO Assembly in September 2010”, emphasising the risk of slippage from timetables to set formal emissions targets for the aviation industry.
3. ECONOMIC BENEFITS OF REDUCED WEIGHT

When considering the value that auxetic balance technology could bring to the commercial aviation industry, we begin by considering the value chain, extending from carbon-fibre-reinforced plastic (CFRP) component producers through to the very end consumers, the passengers on board the resulting aeroplanes.

![Figure 3: Extended CFRP value chain (Source: GCG, UCL).](image)

Although auxetic technology is applied at the earliest stages of the aircraft value chain, demand for its inclusion comes from airlines that face tightening government regulation, and ultimately end customers who must pay for fuel, maintenance, etc. through ticket prices. Thus, while materials flow forward in the value chain, customer influence commonly flows ‘backwards’, with the government also having an impact on the industry through passenger taxation and airline regulation.

The aircraft producers form a ‘nexus of influence’ who are required to understand airlines’ concerns and who have the resources and market power to push for the introduction and certification of new technologies through established supply chains. These should be the target for innovators of new intellectual property whose path may otherwise be blocked by inertia, or worse, active discrimination against new developments by established supply chain participants.

As suppliers to the airlines, aircraft producers seek to develop products that offer lower costs of ownership across the lifecycle, while maximising passenger appeal and operating flexibility. The total cost of ownership includes factors such as the original investment cost (whether paid via outright purchase or finance/operating lease arrangements), the cost of day-to-day operations as well as periodic maintenance costs. Any technology that can favourably shift the net effect of the various costs will be of interest to airlines and thus aircraft producers.

Figure 4 illustrates how the costs of operating an aircraft or aircraft fleet, may be broken down into direct and indirect components.
We can expect the items depicted in bold to be impacted on by a reduction in aircraft weight, leading to potential savings for the airline if the operating and maintenance cost items outweigh any increased purchase cost appropriately discounted over the life of the aeroplane.

Having identified fuel, landing/airport charges and maintenance part costs as sources of savings, it is useful to put these into the context of the basket of costs faced by a typical airline. Figure 5 below illustrates the relative scale of these three cost items for a range of airline operating models.

As can be seen, fuel is typically the second largest cost item after the initial purchase cost and in the case of long haul operators is more expensive than flight crew. Total maintenance charges average 11% of operating costs, while airport charges constitute 5-12% of costs, depending on routes flown and terminals used.

Figure 4: Aircraft operating life cycle cost breakdown (Source: IATA, ICAO, US DOT).
We consider the impact of weight reduction on each of these three cost items in turn.

### 3.1 Fuel Consumption

Airframe weight is central to the balance of forces acting on an aircraft. An aircraft in level flight at a constant speed is subject to four forces in balance: lift, thrust, weight (effect of gravity), and drag (see Figure 6).

Figure 6: Four forces acting on an aircraft.

Thrust, provided by the engines, is used to move the aeroplane forward by counteracting drag. Drag itself occurs in two forms. The first, *induced drag*, is a byproduct of the lift generated to
support the aircraft in the air and occurs because the wing produces a lift vector that acts primarily upwards but also (at positive angles of attack) backwards towards the tail of the plane. The second form, parasitic drag, is caused by air friction and turbulence as the aircraft moves air out of its way, through the actions of air flowing across the wing sections which induce vortices at the tips.

These two forms of drag share a differing relation with speed, which explains the impact of weight on aircraft performance. While induced drag is the primary source of drag at slow speeds and high angles of attack, it diminishes in importance relative to parasitic drag as aircraft speeds increase. Induced drag shares an inverse square relation with speed, whereas parasitic drag shares a square relation with speed.

![Figure 7: Composition of drag on an aircraft](Source: J. Heyman (2008). *Basic Structural Theory*. Cambridge University Press.)

As extra weight affects only induced drag through the need to provide additional lift, it can be seen that aerodynamic performance is of greater importance at typical (0.8-0.9 Mach) operating speeds. Parasitic drag is the primary factor affecting thrust requirements at the operating speeds of commercial airliners.

Particularly in the cruise, relatively little of the fuel burnt is used to overcome the weight of the airframe. However, as a source of efficiency improvement, after much work with computational fluid dynamic (CFD) techniques in the 1970-90s, advances in aerodynamics are now reaching the point of diminishing returns, re-emphasising the importance of weight saving.
It has not been possible within the scope of this report to empirically examine the relationship between weight and fuel consumption of typical commercial aircraft. This information is known precisely by manufacturers and used widely by airline customers, but is not published for general use. Instead we have been reliant on previous studies conducted for aviation-related bodies whose purpose has been primarily associated with modelling environmental impacts of aircraft flights.

Whilst initially tempting to simply look at the relative fuel consumption rates of aircraft of varying weights, this ignores the fact that aircraft of differing weights will also have different frontal areas, aerodynamic profiles, engine outputs and typical cruising speeds. To correct for these factors it is necessary to isolate just the impact of weight, keeping all other aircraft parameters constant. The only work to have done this across aircraft types is quoted in the EUROCONTROL (2007) study of aviation cost benefit analyses. Here a mathematical model (‘Lido’) is used to estimate fuel consumption for a range of common passenger aircraft in the en-route and arrival management flight phases at payload levels of 50%, 65% and 80%. The same study also includes data on Dry Operating Weight (DOW) and Maximum Take Off Weight (MTOW) for the same panel of aircraft, allowing calculation of the relationship between absolute weight change and fuel consumption. In Figure 8 we illustrate the effectively linear relationship between payload and fuel consumption across all aircraft types derived from the EUROCONTROL data.

---

Figure 8: Graph of fuel consumption at varying operating weights (Source: EUROCONTROL, UCL).
The payload range of 50% to 80% equates to a range of approximately 85-95% of MTOW. As can be seen from the larger scale plot in Figure 8 below, the relationship between takeoff weight and fuel burn is essentially linear, allowing us to employ linear regression to quantify the potential impact of weight loss on fuel savings.

![Figure 8: Fuel burn by operating weight of aircraft.](image)

The slope of the lines above gives the rate of change of fuel consumption (kg/hr) for a kilogramme change in takeoff weight. This falls in the range 0.03-0.05 kg per hour for the en-route phase dependent on aircraft type, i.e. every kg of weight lost saves 3-5% of its own weight every hour in fuel. Figure 9 below illustrates how the line slope (and hence the fuel burn reduction per kilogramme of weight saved) is clustered in the 0.03 to 0.05 range.
This result can be interpreted in absolute weight terms also for particular aircraft. For instance, for a mid-size jet such as a Boeing 757-200, a 1 tonne reduction in weight improves fuel economy by around 1% in the cruise. For smaller aircraft, e.g. Boeing 737-300, this figure rises to 1.6%.

More generally, we find that the estimated elasticity of fuel consumption with respect to weight for a typical commercial aircraft is 0.9. This figure is consistent with that presented in other sources that have examined the relationship between weight and fuel consumption.

While the EUROCONTROL data is concerned with the en-route flight phase, there are commonly understood to be 5 phases to a commercial flight (Figure 10). However, EEA data suggests that the en-route (or ‘cruise’) phase accounts for 85% to 93% of a typical operational flight, as illustrated in Figure 11.

---

**Figure 9:** Effect of reduced weight in the en-route phase. NB omits turboprop aircraft for clarity.

**Figure 10:** Five commonly identified flight phases (Source: European Environment Agency).

---

8 Capehart B. ‘Encyclopaedia of Energy Engineering and Technology’ (2007), p.27, “A 1% reduction in weight results in a 0.75% to 1% reduction in trip fuel, depending on engine type.”

Figure 11: Estimated fuel consumption by flight phase (Source: European Environment Agency, 2009).

While the relative importance of an individual phase is sensitive to overall flight distance, changing flight distance does not restrict the usefulness of the en-route phase for fuel consumption estimates. Indeed, as can be seen in Figure 12 below, for all but the shortest trips en-route fuel consumption constitutes more than 80% of total flight fuel use; and for larger aircraft, which are most likely to be replaced with more fuel efficient designs, the en-route phase accounts for over 95% of flight fuel over typical operational distances.

Figure 12: Proportion of flight fuel used in the Climb-Cruise-Descent phase.

Notwithstanding the above, it remains the case that fuel savings are achievable from reduced airframe weight throughout the flight, although given the available data from previous studies we are unable to extend quantification of the benefits into all flight phases.
3.2 Maintenance

A second source of potential savings on offer to operators of reduced-weight aircraft is in maintenance costs, which comprise some 8-12% of airlines’ total direct operating costs (see Figure 5). It may be expected that all parts of the aircraft which are subject to loads imposed by the mass of the structure would undergo less wear and thus require less maintenance if that mass were reduced. This is particularly the case for landing gear assemblies, which endure the shock load of the aircraft on landing, and tyres which must be sized on the basis of a particular aircraft mass to spin up to working speed safely in under a second.

Putting a figure on the potential savings available is made more difficult however, by i) the poor availability of detailed maintenance cost data, and ii) the wide variability of maintenance spending by airlines running differing aircraft, route lengths and in-house/outsourced maintenance models. We present below a comparison of US airlines’ cost returns\textsuperscript{10}, which suggests airframe maintenance comprises 30-50% of total maintenance costs. As might be expected, short haul operators with frequent landings per flight hour have the highest relative airframe maintenance charges.

**Figure 14:** Maintenance cost allocation by major component, US airlines (Source: IATA).

However, ‘airframe maintenance’ is a wide-ranging cost category, including work on many items unrelated to aircraft weight: airframe inspections, avionic upgrades, environmental controls, interior refurbishment and hydraulic/fuel line systems. The extent of savings achievable from purely weight-affected items such as landing gear, tyres and brakes is difficult to determine and unlikely to be above 5% of total maintenance cost.

Thus it can be seen that while maintenance savings would undoubtedly be used by aircraft producers to help sell the concept of a reduced-weight aircraft, the savings achievable from, for

\textsuperscript{10}IATA MCTF ANALYSIS - FY2007 “Airline Maintenance Cost Report”, as compiled from DOT Form 41.
instance, a 10% weight saving in relation to total airline operating costs, would be very small. We estimate that in practice these would be no more than 0.5%.

This estimate does not take into account any additional costs or savings obtainable as a direct result of a switch from steel/aluminium construction to carbon fibre. These may occur through reduced periodic inspection costs or increased service and repair costs. It has not been possible to identify accurately the scale or extent of such additional cost implications here.

### 3.3 Airport Charges

A third source of savings arises because many airports use aircraft weight as a proxy for size when setting landing and parking charges. Although charges are also made for electricity used, check-in counter use and other fees which are priced on a per-passenger basis, it is aircraft weight fees that predominate within the aircraft-only charges. Athens International is a typical example:

![Figure 15: Airport charges per LTO (Landing and Take Off) cycle at Athens International, 2009](Source: Athens International Airport, UCL).

The green numbers in the graph above indicate the proportion of a landing and take-off cycle charges directly related to MTOW for a range of aircraft. We can see that airport charges are moderately sensitive to aircraft weight in the case of Athens. Indeed, above commuter jet sizes, we estimate that a 1% decrease in weight leads to a 0.35% - 0.45% reduction in total airport charges. This analysis includes per-passenger charges, assumed to be treated as cost pass-throughs by the operator in ticket prices.
However, Frankfurt provides a counter-example of an airport whose charging regime is largely insensitive to aircraft weight. Figure 16 below illustrates the elasticity of total airport charges with respect to weight for the aircraft types depicted above at these two airports.

![Figure 16: Elasticity of total airport charges to aircraft MTOW at Athens and Frankfurt international airports (Source: UCL).](image)

It is clear that when serving a mixed fleet of older (heavier) and newer (lighter) planes, operators utilising planes with higher composite content will benefit from reduced landing and parking charges on a per passenger basis. However, with relatively fixed cost structures, this benefit will persist only until airport operators act to counter revenue losses from lighter planes by increasing per tonne charges for such aircraft. In the absence of other measures, this could be expected to occur shortly after the widespread introduction of weight-reduced aircraft, making this cost benefit transitory only for operators.

Incentives could be introduced by governments to subsidise an ongoing reduction in airport charges for lower weight aircraft in an attempt to stimulate their use. But to be effective, initiatives of this type would need to be widespread and coordinated, making them perhaps best suited to refinements of international treaty round agreements.

Further work to develop this analysis is desirable, although this is hampered by airport charging schedules not being publicly disclosed or subject to individual negotiation with customer airlines.
Summary

The analysis conducted thus far allows us to reach some preliminary conclusions regarding the impacts on aircraft weight reduction in the airline industry.

We estimate that a 10% weight saving would lead to:

- A 9% reduction in fuel costs over a typical mid- to long-haul route
- A 0.5% projected reduction in maintenance costs
- Up to 4% reduction in airport charges (until such charges are rebased)

This implies that aircraft producers can offer a typical UK airline a 0.15% saving in total operating costs for every 1% trimmed from aircraft mass. The majority of these savings would come from reduced fuel use.

Expressed in terms of seat-km costs, a 9% reduction in fuel costs would have had a modest impact in airline costs over the period 2006–2009:

![Operating cost per seat km, selected airlines (Source: UCL).](image)

*Figure 17: Operating cost per seat km, selected airlines (Source: UCL).*
As expected, the effect is most pronounced for long-haul carriers that have a greater proportion of their overall operating costs associated with fuel. Higher long-term fuel costs will exacerbate this effect.

However, when considering the benefit of future weight saving technologies, we must consider their speed of introduction into the overall world aircraft fleet. Such an analysis forms the basis of the next section of this report.
4. APPLICATION TO THE FUTURE AIRLINE FLEET

Commercial airliners are typified by high initial purchase costs, designed-in durability and a customer desire for commonality amongst aircraft fleets. As such, they have service lives frequently in excess of 20 years, extending to beyond 30 years for larger aircraft. So while technology introductions may improve the performance of aircraft added to the fleet more recently, assessing the benefits of such technology means recognising that operators cannot replace entire fleets rapidly. An estimate must be made of the speed of introduction of new aircraft types, their penetration into the overall aircraft pool and their share of flying hours against existing models.

It has not been possible within a study of this scope to forecast the share of newly introduced aircraft into overall passenger kilometres flown. Factors such as individual route incidence, route length, airline propensity to buy, passenger configurations, fuel cost, and many other variables would be required to attempt a comprehensive forecast of future aircraft use by passenger km. However, it has been possible to estimate the delivery volumes of existing technology aircraft and, by putting these in the context of overall market growth, estimate the numbers of future aircraft required to meet demand. Such future aircraft present an opportunity for the introduction of new weight saving technology, in that outline estimates of the impact of weight saving can be made for aircraft deliveries. By making a number of assumptions around the rate of retirement of aircraft within the current fleet, we can produce a simplified forecast of the constitution of the future aircraft pool.

We have estimated passenger fleet deliveries by aircraft type, with overall volumes consistent with Airbus forecasts for fleet size, growth rate and constitution. This allows us to capture the longevity of current models employing current production methods (<30% composites) as well as the introduction of the latest designs (B787, A350) with significant CFRP content.

**Figure 18:** Breakdown of global fleet growth (Source: Airbus).

It also allows for the recognition of the time taken to introduce designs with newly-certified materials technology. Airbus forecasts\(^1\) estimate that the global fleet of commercial aircraft with over 100 seats will increase from 14,016 at end 2008 to 28,111 by end 2028, as shown below.

\(^{11}\) Airbus, Global Market Forecast (2009)
Airbus forecast that 880 of the aircraft currently in service with operators will remain in present use by 2028 and a further 3,134 will be recycled to other airlines over the next 20 years. The balance of the current fleet will either be converted to cargo freighter use (2,585 aircraft) or scrapped/mothballed altogether (7,417 aircraft). These aircraft must be replaced to maintain current fleet capacity. In addition, passenger volume growth over the 2008-2028 period will require a further 14,095 entirely new aircraft. In total 24,097 new aircraft will need to be delivered over the next 20 years to meet passenger demand.

Airbus’ detailed demand forecasts aim to identify future needs by aircraft size category. Forecasts are produced for aircraft from 50 seats upwards, although with Airbus’ products not targeting the sub-100 seat segments, detail is only provided for aircraft above 100 seats.

Broadly, ‘Single Aisle’ (SA) aircraft equate to Boeing 737-size models, ‘Small Twin Aisle’ (STA) refers to aircraft in the A300 or Boeing 767 category which has become less popular in recent years, being replaced by ‘Intermediate Twin Aisle’ (ITA) aircraft with wider bodies and extended range operations such as the A340 and Boeing 777. Finally, ‘Very Large Aircraft’ (VLA) are those with over 350 seats and currently comprise only the Airbus A380 and Boeing 747. There are no new aircraft in this category currently planned.

In Figure 20 we estimate delivery volumes by model type for commercial aircraft with over 100 seats. This assumes no new entrants into the large aircraft space and no significant macroeconomic shocks to cause the Airbus forecasts, on which delivery volumes by category are based, to be revised.
### Deliveries

#### World Wide Fleet (end year, Airbus prediction)

<table>
<thead>
<tr>
<th>Type</th>
<th>MTOW (t)</th>
<th>Carbon Fibre content</th>
<th>Total '09-28 deliveries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singles Aisle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airbus A318</td>
<td>39.3</td>
<td>59.9% 6% SA</td>
<td>17 13 5</td>
</tr>
<tr>
<td>Airbus A319</td>
<td>40.6</td>
<td>64.0% 6% SA</td>
<td>105 98 84</td>
</tr>
<tr>
<td>Airbus A320</td>
<td>42.4</td>
<td>73.5% 6% SA</td>
<td>194 189 184</td>
</tr>
<tr>
<td>Airbus A321</td>
<td>46.2</td>
<td>83.0% 5% SA</td>
<td>51 66 84</td>
</tr>
<tr>
<td>Boeing 737-MG</td>
<td>47.4</td>
<td>78.0% n/a</td>
<td>736 580 355</td>
</tr>
<tr>
<td>Category total</td>
<td></td>
<td></td>
<td>4,556 14,794</td>
</tr>
<tr>
<td>Singles Aisle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airbus A320</td>
<td>109.0</td>
<td>171.7% 1% STA</td>
<td>6 - -</td>
</tr>
<tr>
<td>Airbus A330</td>
<td>115.7</td>
<td>268.9% 16% STA</td>
<td>11 13 8</td>
</tr>
<tr>
<td>Airbus A332</td>
<td>132.2</td>
<td>326.9% 3% STA</td>
<td>68 72 69</td>
</tr>
<tr>
<td>Boeing 787</td>
<td>153.1</td>
<td>304.1% 3% STA</td>
<td>12 12 13</td>
</tr>
<tr>
<td>Category total</td>
<td></td>
<td></td>
<td>456 4,097</td>
</tr>
<tr>
<td>Intermediate Twin Aisle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airbus A340</td>
<td>177.8</td>
<td>368.0% 3% ITA</td>
<td>14 8 11 13 8</td>
</tr>
<tr>
<td>Airbus A350</td>
<td>235.4</td>
<td>556.0% 16% ITA</td>
<td>0 - - -</td>
</tr>
<tr>
<td>Boeing 777</td>
<td>167.8</td>
<td>251.5% 11% ITA</td>
<td>307 78 83 61 78</td>
</tr>
<tr>
<td>Boeing 787</td>
<td>114.5</td>
<td>219.5% 31% ITA</td>
<td>840 0 - -</td>
</tr>
<tr>
<td>Category total</td>
<td></td>
<td></td>
<td>1,654 1,765</td>
</tr>
<tr>
<td>Very Large Aircraft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airbus A380</td>
<td>276.8</td>
<td>568.0% 21% VLA</td>
<td>180 38 1 12 14 24</td>
</tr>
<tr>
<td>Boeing 747</td>
<td>164.4</td>
<td>428.3% 1% VLA</td>
<td>112 13 16 14 7 6</td>
</tr>
<tr>
<td>Category total</td>
<td></td>
<td></td>
<td>292 1,318</td>
</tr>
</tbody>
</table>
| Total deliveries (all categories) | | | 894 848 924 1,076 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,112 1,112 1,112 1,112 1,112 1,112 1,112 1,112 1,112 1,112

#### Summary current + future generation aircraft

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Singles Aisle</td>
<td></td>
<td></td>
<td></td>
<td>194</td>
<td>189</td>
<td>184</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Airbus A320</td>
<td>109.0</td>
<td>171.7% 1% STA</td>
<td>6 - -</td>
<td>12</td>
<td>12</td>
<td>13</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airbus A330</td>
<td>115.7</td>
<td>251.5% 11% ITA</td>
<td>307 78 83 61 78</td>
<td>16</td>
<td>14</td>
<td>7</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category total</td>
<td></td>
<td></td>
<td>1,654 1,765</td>
<td>16</td>
<td>14</td>
<td>7</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very Large Aircraft</td>
<td></td>
<td></td>
<td></td>
<td>894 848 924 1,076 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093 1,093</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 20:** Estimated deliveries of commercial aircraft over 100 seats (Source: Airbus, Boeing, UCL).
We make the following assumptions in deriving a future aircraft delivery schedule and forecast operating mass of the global airline fleet:

1. At its core, our fleet delivery assumption is based on Airbus’ forecast for global aircraft deliveries for 2018 and 2028.

2. We adopt Airbus’ specification of four categories of aircraft: small aeroplane (SA), small twin aisle (STA), intermediate twin aisle (ITA), and very large aircraft (VLA). Aircraft with configurations smaller than 100 seats, while modelled by Airbus, are not included in this report.

3. Forecast deliveries of the four categories of aircraft are consistent with the Airbus demand forecast for that category for the 2009-18 and 2019-28 periods. In the absence of compelling data to support a typical delivery profile over aircraft model life, we assume a linear delivery rate consistent with the overall Airbus category volumes. This occurs despite there not necessarily being a competitive offering from either Airbus or Boeing available on some occasions in some categories (an issue not addressed by Airbus in its forecasts).

4. The dry operating weights of the four aircraft categories are the weighted average of all current Airbus and Boeing models in that category, weighted by their 2009 delivery volumes.

5. Dry operating weight and maximum take-off weight information for the underlying models at the beginning of our forecast is obtained from manufacturers’ own data. Typical take-off weights for the four aircraft categories are derived by the weighted average method used in assumption 4, plus an assumed payload level.

6. A typical payload of 72%, consistent with recent literature on load factors in commercial aviation (see Figure 21). The available payload is calculated as the difference between dry operating weight and MTOW.

---

12 Includes weight of structure, powerplant, furnishing systems, unusable fuel and other unusable propulsion agents, and other items of equipment that are considered integral to a particular airplane configuration. Also included are certain standard items, personnel, equipment, and supplies necessary for full operations, excluding usable fuel and payload.
7. The maximum target carbon fibre composition of an aircraft is assumed to be 40% of its dry operating weight by 2020 (in line with IATA’s commitment on emissions reductions). Boeing 787 currently contains the highest industry CFRP content of 31% by weight. For the period 2020-2028, it is assumed that the carbon fibre composition increases linearly 2% every year.

8. CFRP is assumed to save 20% of the weight of the material it replaces. Broughton, Beevers and Hutchinson (1999) state that carbon-fibre-reinforced plastic (CFRP) theoretically produces weight savings of 33% when compared to aluminium. We use 20% rather than 33% because certain parts of established aircraft designs will not be readily replaced entirely with new materials at theoretical minimum weights, thus the use of a more conservative number.

9. In 2014, five years after the report period begins, weight savable (or “applicable”) CFRP (carbon fibre that is suitable for adoption of weight saving techniques, for example auxetic balancing) is assumed to enter the aviation market. At this point, we assume that 50% of the CFRP is weight savable. Following proof of the suitability of weight savable composites in aviation use, in 10 years (2019), we assume 100% of carbon fibre structures convert to weight savable CFRP.

10. Of the existing fleet at end 2008 there are 10,002 aircraft that are neither recycled nor remain in service; these are scrapped at a linear rate until 2028.

11. The average weight of a scrapped aircraft is 108 tonnes, consistent with the average operating weight of an aircraft delivered in 2009. While aircraft scrapped later may be lighter for a similar volume, they are also likely to be on average larger (more seats); the effect of these two are assumed to cancel one another out to leave 2009 average weights applicable to the historic fleet.

12. New deliveries and aircraft replacements are added and subtracted, respectively, from fleet weight once a year.

The delivery forecast can be summarised in the following chart, illustrating volumes delivered by size category across manufacturers.

**Figure 22:** Forecast evolution of commercial aircraft deliveries (over 100 seats) (Source: UCL).

Given this schedule of forecast deliveries and estimated dry and MTOW weights, we estimate the future fleet operating weight. While new deliveries will, by 2028, constitute the majority of the global fleet, it is important that continuation of the existing fleet is correctly modelled to ensure an appropriate pace of technology adoption.

---


Figure 23: Resultant forecast of aircraft deliveries by take-off weight, assuming no carbon fibre weight abatement measures  (Source: UCL).

Having made these assumptions, one can derive an estimated fleet weight for each year over the period 2009-2028. With the end-2008 fleet estimated to weigh approximately 1.51 Mt, we forecast future fleet weight based on a range of potential weight savings applied to the applicable CFRP content of future aircraft. The tables below summarise the fleet mass for 2018 (after the effects of initial 50% adoption of weight saving techniques introduced in 2014) and for 2028 (following universal use of weight saving in all CFRP elements).

Figure 24: Fleet weight estimates produced from delivery forecasts and fleet replacement assumptions  (Source: UCL).

### 2018 Fleet Weight Estimate ('000 t)

<table>
<thead>
<tr>
<th>Applicable CFRP content by weight</th>
<th>2019</th>
<th>0%</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%logan</td>
<td>2,308</td>
<td>2,304</td>
<td>2,300</td>
<td>2,296</td>
<td>2,291</td>
<td>2,287</td>
<td>2,283</td>
<td></td>
</tr>
<tr>
<td>10%logan</td>
<td>2,307</td>
<td>2,302</td>
<td>2,297</td>
<td>2,292</td>
<td>2,287</td>
<td>2,281</td>
<td>2,276</td>
<td></td>
</tr>
<tr>
<td>20%logan</td>
<td>2,306</td>
<td>2,300</td>
<td>2,294</td>
<td>2,288</td>
<td>2,282</td>
<td>2,276</td>
<td>2,270</td>
<td></td>
</tr>
<tr>
<td>30%logan</td>
<td>2,305</td>
<td>2,298</td>
<td>2,291</td>
<td>2,284</td>
<td>2,277</td>
<td>2,270</td>
<td>2,263</td>
<td></td>
</tr>
<tr>
<td>40%logan</td>
<td>2,305</td>
<td>2,296</td>
<td>2,288</td>
<td>2,280</td>
<td>2,272</td>
<td>2,264</td>
<td>2,256</td>
<td></td>
</tr>
<tr>
<td>50%logan</td>
<td>2,304</td>
<td>2,294</td>
<td>2,285</td>
<td>2,276</td>
<td>2,267</td>
<td>2,258</td>
<td>2,249</td>
<td></td>
</tr>
<tr>
<td>60%logan</td>
<td>2,303</td>
<td>2,292</td>
<td>2,282</td>
<td>2,272</td>
<td>2,262</td>
<td>2,252</td>
<td>2,243</td>
<td></td>
</tr>
</tbody>
</table>

### 2028 Fleet Weight Estimate ('000 t)

<table>
<thead>
<tr>
<th>Applicable CFRP content by weight</th>
<th>2028</th>
<th>0%</th>
<th>15%</th>
<th>25%</th>
<th>35%</th>
<th>45%</th>
<th>55%</th>
<th>65%</th>
<th>75%</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%logan</td>
<td>3,089</td>
<td>3,075</td>
<td>3,062</td>
<td>3,048</td>
<td>3,035</td>
<td>3,022</td>
<td>3,009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%logan</td>
<td>3,087</td>
<td>3,073</td>
<td>3,058</td>
<td>3,044</td>
<td>3,030</td>
<td>3,017</td>
<td>3,003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%logan</td>
<td>3,086</td>
<td>3,071</td>
<td>3,055</td>
<td>3,041</td>
<td>3,026</td>
<td>3,011</td>
<td>2,997</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30%logan</td>
<td>3,085</td>
<td>3,068</td>
<td>3,052</td>
<td>3,037</td>
<td>3,021</td>
<td>3,006</td>
<td>2,991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40%logan</td>
<td>3,083</td>
<td>3,066</td>
<td>3,049</td>
<td>3,033</td>
<td>3,017</td>
<td>3,001</td>
<td>2,985</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50%logan</td>
<td>3,082</td>
<td>3,064</td>
<td>3,046</td>
<td>3,029</td>
<td>3,012</td>
<td>2,996</td>
<td>2,979</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60%logan</td>
<td>3,081</td>
<td>3,062</td>
<td>3,043</td>
<td>3,025</td>
<td>3,008</td>
<td>2,990</td>
<td>2,973</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We develop three scenarios for modelling the effects of new technology to reduce the mass of CFRP on future aircraft.

**Scenario 1:** No change (base)

**Scenario 2:** 30% weight saving on applicable CFRP, beginning 2014

**Scenario 3:** 50% weight saving on applicable CFRP, beginning 2014
The evolution of fleet weight under these assumptions is depicted below.

**Figure 25:** Forecast fleet weight under varying CFRP weight saving assumptions  (Source: UCL).

As Figure 25 indicates, the time taken to introduce any weight saving technology into aircraft with increasing future carbon fibre content means the benefits are not noticeable until around 2020. From this point onwards, however, the weight benefit across the fleet is marked, given the longevity of such aircraft which will then go on to constitute much of the working fleet.

Translating this into fuel savings is straightforward if we adopt the fuel/weight elasticity estimate of 0.9 from Section 3. The table below summarises the effect of the two weight saving scenarios on fuel consumption across the fleet at two time points:

<table>
<thead>
<tr>
<th></th>
<th>Fleet Weight ('000s t)</th>
<th>Incremental weight reduction over base</th>
<th>Incremental fuel consumption saving over base</th>
</tr>
</thead>
<tbody>
<tr>
<td>No weight savings to CFRP (base)</td>
<td>2,480  3,231</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>30% weight reduction in applicable CFRP after 5 years</td>
<td>2,445  3,110</td>
<td>1.4%  3.8%</td>
<td>1.3%  3.4%</td>
</tr>
<tr>
<td>50% weight reduction in applicable CFRP after 5 years</td>
<td>2,421  3,029</td>
<td>2.4%  6.3%</td>
<td>2.1%  5.6%</td>
</tr>
</tbody>
</table>

**Figure 25:** Summary benefits of fleet weight reduction under three scenarios  (Source: UCL).
Note CO₂ benefits are the same relative size as fuel consumption savings, as carbon dioxide is produced in a fixed ratio to fuel burned.

It can be seen that, although the benefits of any new weight saving technology take time to come through, by the time they have adequately penetrated the working fleet of aircraft the fuel savings are significant. Quantification of these benefits in dollar terms is complicated by the need to take account of changing flight distances, differential utilisation of newer aircraft on longer routes and future fuel price evolution. Nevertheless, the potential for savings from a universally adopted carbon fibre weight saving technology are readily apparent.
5. CONCLUSION AND NEXT STEPS

We have sought to identify in this report the sources of savings achievable by operators of commercial aircraft with reduced-weight carbon fibre components. We observe that the industry background is characterised by worldwide growth in passenger travel which will drive sustained demand for new airliners. Airlines demand that these aircraft be lighter, more fuel efficient, and offer lower service costs and reductions in per-passenger emissions.

In addition, inter-governmental agreements such as successors to the Kyoto Treaty will increasingly seek to target air transport and its emissions. This provides further impetus to aircraft manufacturers to develop aircraft: /with fewer carbon emissions/which are increasingly carbon neutral/with environmentally approved emissions reductions/ for sale to their customer airlines. The responsibility of governments to meet the targets to which they have agreed may lead to a willingness to financially support the development and adoption of weight-reduction technologies, a potential upside for airlines that has not been examined here.

The central benefit of lower weight will be felt in lower fuel consumption, of ever-higher importance given rising fuel prices. Fuel savings are estimated to occur at 90% of the proportionate change in aircraft mass. Other benefits include lower airport charges in the short term and potentially some maintenance savings, although these have been difficult to quantify and are likely to be small.

Of the 14,000 aircraft in current fleet of commercial aircraft with over 100 seats, only 4,000 will still be in use by 2028, with expanding passenger volumes and retirement of existing aircraft creating a demand for about 24,000 new aircraft. This provides a substantial demand base for the profitable development and introduction of innovative technology in new designs.

We estimate that the current fleet weighs in the region of 1.5 million tonnes and that in the absence of any weight saving measures this will rise to 3.2 million tonnes by 2028. Using assumptions of future carbon fibre use, we believe that a 30% weight saving to an assumed 50% of applicable CFRP content on designs introduced after 2018 will allow overall fleet weights to fall 3.8% (relative to no-weight savings in CFRP content), leading to a 3.4% reduction in fuel use. More aggressive assumptions about the potential weight savings in applicable carbon fibre parts (50% CFRP weight savings with CFRP content rising to 45% by weight) imply a 6.3% reduction in fleet mass and 5.6% fall in fuel use.

Carbon dioxide production would be impacted in direct proportion to fuel use, meaning that the introduction of any significant weight saving technology could play a meaningful role in attenuating future CO₂ emissions.

This analysis has throughout concerned itself with estimating the cost benefits available from a reduction in aircraft weight. We believe this is the correct approach, rather than estimating the extent of additional revenues from additional payload capacity made available. We believe that airlines currently work to ensure maximum loading of aircraft currently in service and that were weight to be lost from the structure of these planes, configuration limits would not allow for any incremental passenger space. This assumption may be relaxed in future research incorporating new aircraft designs, as we describe below.
Next Steps

The introduction of auxetic balance technology, if sponsored by a major aircraft producer, would be a gradual process taking 5-10 years following development of the technique before full scale, certified aviation use. For investors viewing a payback over such an extended horizon, more information on the timing, precision and extent of cost savings available to the end market is essential to support any investment proposal.

To further strengthen the case for investment in a weight reduction technology such as auxetic balancing we would seek to:

- Develop the future fleet evolution analysis to derive an aggregate fuel consumption estimate in absolute terms for the period 2009 to 2028. The current analysis merely forecasts fleet weight and ignores how the aircraft will be used differently to today. Assumptions or data for route length, passenger capacity, engine efficiency, aerodynamic improvements, routing optimisation, and cargo load factors, amongst others, would all be required for this next step.

- Incorporate fuel use information or develop practical assumptions for all flight phases.

- Comment on the cost of increased carbon fibre content, both at the initial purchase phase and in terms of ongoing maintenance, an issue that the commercial aviation sector itself is unlikely to have all the answers to at this point.

- Incorporate the impact of new designs allowing significantly higher passenger loads in traditionally sized aircraft, owing to improved aerodynamic design coupled with radically new fuselage configurations.