nature climate change

SUPPLEMENTARY INFORMATION

DOI: 10.1038/NCLIMATE2865

Costs of mitigating CO_2 emissions from passenger aircraft

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The supplementary material consists of a brief summary of government and industry action on controlling air transportation CO_2 emissions, Table S1 reporting key US air transportation system characteristics in 2012, and a more detailed account of the 21 measures for reducing CO_2 emissions from narrow body aircraft that underlie this study.

Government and Industry Action on Controlling Air Transportation CO_2 Emissions

Since the early 2000s, governments and industry have explored, specified, or introduced policies or targets to control air transportation CO_2 emissions. In 2003, the European Commission Directive 2003/87/EC specified the quantity of CO_2 emissions allowances for aviation and related issues.[1] This document was one of the foundations for the inclusion of aviation into the European Emissions Trading System starting in 2012.[2] Thereafter, the International Air Transport Association (IATA) and the US Federal Aviation Administration (FAA) defined a carbon-neutral growth target from 2020. In addition, IATA targets a 50% reduction of net CO_2 emissions by 2050 compared to 2005 levels, whereas the FAA aims to reduce the climate impact of all aviation emissions relative to their 2005 levels over the same period.[3,4] Meanwhile, the

International Civil Aviation Organization (ICAO) has begun to develop aircraft CO_2 emission standards for new aircraft types and explore a global, market-based mechanism on international routes.[5,6] Most recently, the US Environmental Protection agency has started a process to regulate aircraft CO_2 emissions.[7]

Table S1 Average and Total Air Transportation System Characteristics for Passenger Aircraft Operating in US Domestic Service in 2012

	Effective Fleet	Seats per Aircraft	Stage Length km	No. PAX Mln	RPK Bln	PAX Load Factor	A/C Departures Mln	Block Speed km/h
Turboprop	[1]134	59	376	13.7	5.1	0.74	0.31	326
Jet A/C								
50-99	1,567	60	784	136.1	106.7	0.79	2.88	475
100-189	2,698	149	1,456	497.0	723.7	0.84	3.98	603
190-299	120	240	2,939	21.5	63.3	0.87	0.10	697
300+	7	326	4,025	1.5	6.1	0.83	0.01	762
US Domestic	4,525	128	1,167	669.9	904.9	0.83	7.29	559

	Aircraft Utilization h/day	Airborne / Block h %	Fuel Use Bln Gal	Energy Intensity MJ/RPK	Total CO_2 Emissions Mln tonnes	Direct Operating Costs US¢/RPK
Turboprop	7.4	78	0.09	2.21	0.8	18.0
Jet A/C						
50-99	8.3	85	2.11	2.60	20.4	12.9
100-189	9.8	85	7.82	1.42	75.4	7.2
190-299	10.0	94	0.65	1.34	6.2	6.7
300+	11.8	89	0.05	1.13	0.5	5.2
US Domestic	9.2	85	10.72	1.56	103.3	9.1

Tables Notes:
Source: *Ref.8*.
The 100-189 seat class corresponds to the narrow body aircraft analysed in this study. [1]Fleet size of turboprops likely to be underestimated, as the underlying Form 41 database excludes small carriers.

Measures for Reducing Narrow Body Aircraft CO_2 Emissions

Technology Measures

This set of measures consists of five retrofit measures for introduction starting in 2015, one intermediate aircraft type (A320NEO / B737MAX / Bombardier CSeries) projected to be introduced from 2016 on, and two next-generation aircraft types that could be available in 2035. Table 1 summarizes the key characteristics.

Blended Winglets

Retrofitting blended winglets to existing aircraft increases the lift-to-drag ratio through a higher wing aspect ratio and thus reduced induced drag. Although these wingtip devices increase an aircraft's structural weight, the improved aerodynamics result in payload-range benefits and a net fuel burn reduction of 2-4% for a B737 for stage lengths of 1,000-5,000 km.[9,10] Taking the average narrow body aircraft without blended winglets operating in 2015 as a reference, a 3% fuel burn reduction translates into fuel savings of 83,000 gallons per aircraft per year (with fuel use and effective fleet data from Table S1) or $247,000 (assuming the 2012 fuel price of $3.1 per gallon). Exploiting these benefits requires retrofit expenditures of $750,000 for winglets[10] and installation costs of around $100,000. Because nearly all B737 aircraft operating in the US and suitable for retrofit have already been retrofitted, we apply this measure to the A320 family of aircraft, for which a retrofit program is in place.[11]

Carbon Brakes

Carbon brakes can absorb a larger amount of kinetic energy than steel brakes at greatly reduced weight. The associated weight savings are 250-320 kg for a Boeing 737-600/700.[12,13] Using the aircraft performance model derived rule of thumb that 1,000 kg weight savings reduce narrow body aircraft fuel use by around 1.25% for stage lengths between 900 and 1,900 km, a weight reduction by 250-320 kg would result in a roughly 0.35% decline in fuel use or about 10,000 gallons per aircraft per year, corresponding to $31,000 per year (2012 fuel price of $3.1 per gallon). Based on available industry repair/overhaul cost data[14], the extra annual expenditures would be $30,000 per aircraft per year, resulting in net benefits of $1,000 per year. Because all

Airbus vehicles are already equipped with carbon brakes, we assume that the retrofit potential applies to only B737-NG aircraft with an expected life greater than three years, or 13% of the narrow body fleet in 2015, declining to 10% in 2020.

Re-engining

While the complete replacement of an aircraft engine with a more fuel-efficient model can provide substantial fuel burn reductions, a re-engine program can require modification of virtually every aircraft component and have far-reaching knock-on effects.[15] Partly because of this complexity, there was only one re-engining program in recent history. Yet, the deployment of more fuel efficient turbofan engines for the A320NEO, B737MAX, and Bombardier CSeries families could offer replacement options for existing narrow body aircraft. We assume that the Pratt & Whitney geared turbofan and the CFM International LEAP engine will offer fuel burn reductions of about 12.5%.[16,17] Using the 2012 fuel price of $3.1 per gallon, the associated annual fuel reduction of 363,000 gallons per aircraft would result in annual cost savings of $1.1 million. We employ new engine costs of $12.5 million[18] before a discount of 20%, retrofit costs of $625,000 for both engines[16], and a 20% residual value of the replaced engines. The conversion is carried out during a major maintenance check, thus eliminating the need for leasing an aircraft during that period. In light of our assumption that retrofit-related investments need to be recuperated as an aircraft reaches its mean age of 29 years, the associated long payback time of 15 years implies that only aircraft up to 14 years of age can be considered for engine replacement.

Cabin Weight Reduction

Aircraft weight can be reduced through light-weighting or (partly) removing cabin components, such as seats, galley trolleys, carpets, and other cabin fittings, of which seats offer the largest single weight reduction potential. In addition, lighter-weight and thus thinner seats enable a higher seat density while maintaining the amount of legroom; we did not account for this second-order benefit. We explore two weight reduction cases. A mild reduction case, which includes a reduction of seat weight by one-third, results in a 950 kg weight reduction at extra costs of $300,000.[19,20,21] An aggressive case in which seat weight is reduced by two-thirds results in a weight reduction of 1,700 kg at extra costs of $970,000 (estimate based on *ref 22*). Because a

1,000 kg reduction of aircraft weight causes block fuel burn to decline by about 1.25%, the mild weight reduction would cut annual block fuel burn by 1.2% or 34,000 gallons, while the aggressive weight reduction would translate into a block fuel burn reduction of 2.1% or 59,000 gallons. Under 2015 conditions, the payback times correspond to 2.9 and 5.3 years, respectively. We therefore implement these options in aircraft with a maximum age of 26 and 24 years, respectively. Because the cabin is removed during a major maintenance check, the associated implementation costs are negligible.

Electric Taxiing

According to Table S1, the fleet of US narrow body aircraft operated for nearly 10 million block hours in domestic service in 2012. 15% of that time, i.e., 150,000 hours total or 22 min per flight cycle were spent on the ground with engines running. Using a typical 2-engine taxi fuel burn of 12.5 kg per minute for narrow body aircraft[23], 370 million gallons of fuel were burned by this aircraft size class on the ground, corresponding to 4.6% of total narrow body aircraft fuel use. A large share of that amount of fuel (2.8% per flight cycle) could be saved through electric taxiing systems, that is, electric motors installed in the aircraft wheels, powered by the auxiliary power unit generator (e.g. *ref. 24*), after accounting for the taxiing system's extra weight. According to our estimates, around 77,000 gallons could be saved per aircraft per year, which translates into annual cost savings of $237,000. The additional cost savings, which result from pushbacks with reduced tug operations, lower engine and brake maintenance, reduced foreign object damage, and time savings were estimated to be larger than the additional costs due to increased fuel consumption resulting from the increased weight mentioned above, tire wear, maintenance of the auxiliary power unit and some airframe components.[25] No reliable estimates of capital costs are available, but one exploratory European study concludes that "electric taxiing may well be cost effective on its own economic merits" (*ref. 16*). Moreover, one manufacturer (WheelTug) provides the system and installation for free in return for a share of the cost savings from reduced fuel consumption.[25] We assume that the electric taxi system corresponds to half of the typical landing gear costs or 0.75% of the current-generation aircraft list price, equaling around $500,000.

Next-Generation Narrow Body Aircraft

In addition to the intermediate-generation narrow body aircraft (A320NEO, B737MAX, Bombardier CSeries), we employ two next-generation vehicles for market introduction in 2035.[26] One future vehicle, which is characterized by a high share of composite materials, higher bypass ratio turbofan engines, and increased L/D, provides a fuel burn reduction of around 30% at 22% higher capital costs compared to the current A320 model. The alternative aircraft is propelled with open rotor engines. Its characteristics reflect the average of two alternative designs, (i) a straightforward modification of the next-generation A320, operating at similar speeds, where the main fuel burn benefit results from the open rotor engines' higher propulsive efficiency and (ii) an optimized open rotor engine aircraft that cruises at lower Mach numbers to avoid losses caused by compressibility effects—lower cruise speeds, in turn, allow the use of unswept wings, which are structurally more efficient, and hence lighter than swept wings. Overall, we expect a 40% fuel burn reduction at 44% higher capital costs.

Synthetic Fuels from Cellulosic Biomass

Among the wide range of possible feedstocks, we focus on cellulosic biomass due to their comparative abundance and low impact on the fuel versus food conflict. Cellulosic biomass waste from US agriculture, forests, and urban wood amounted to nearly 230 million tonnes in 2012 and is expected to grow to some 300 million tonnes in 2030.[27] These amounts, which correspond to 3.4-4.4 EJ of biomass, or—using a 50% conversion efficiency of biomass-to-liquids (BTL)—to 13-33 billion gallons of synthetic fuel, are larger than the nearly 11 billion gallons of jet fuel consumed by the US commercial airline fleet in domestic passenger operations in 2012 (see Table S1). Importantly, the consumption of waste-based synthetic fuel would not affect indirect land-use changes that could occur as a result of large-scale plantations of energy crops and potentially enhancing the release of soil CO_2 emissions. The roadside costs of biomass waste are below \$50 per tonne or \$0.4 per gallon of synthetic fuel equivalent. Once the low-cost waste has been utilized, feedstock costs can increase up to \$200 per tonne for conventionally sourced wood or \$3.5 per gallon of synthetic fuel (again using a 50% BTL efficiency). Cellulosic biomass based fuels offer a reduction of lifecycle CO_2 emissions by up to 80-85% compared to petroleum-derived fuels.[28,29]

In the absence of any operating commercial-scale BTL plant, synthetic fuel production costs are highly uncertain. Rough cost estimates suggest synthetic fuel costs to be in the order of $4 per gallon for a small-scale plant following a thermochemical process and using biomass waste. (A synthetic fuel plant with an output of 2,000 bbl per day would require capital expenditures of about $500 million. Using an interest rate of 12% per year and a depreciation period of 15 years, annualized capital costs are $2.45 per gallon. In combination with operation and maintenance costs in the order of 5% of capital costs, pretreatment costs of $0.33 per gallon, total conversion costs are around $3.6 per gallon, excluding feedstock costs).

A compilation of data from forward-looking studies suggests this number to decline over time. For example, the IEA "Technology Roadmap Biofuels for Transport" projects BTL costs to decline from currently $4.4 per gallon to $3.0-3.6 per gallon of jet fuel in 2050.[30] This projected range is roughly consistent with a 2009 US National Academies study that projected the 2020 costs of BTL to range from $3.1 per gallon based on biochemical processes to $3.7 per gallon for jet fuel produced via thermochemical processes.[31] Taking these results into account, we explore a cost range from $3.0-3.6 per gallon, assuming commercial-scale production to start in 2020.

Air Traffic Management Measures

A large number of candidate operational procedures exist which can theoretically be implemented relatively quickly. For example, over 60 operational fuel-saving measures were identified in a recent study.[32] To manage scope, a limited selection of these was considered in this study, covering the majority (estimated over 75%) of the potential benefits. Measures associated with each flight phase were bundled together. In each case, key figures are shown in Table 2. Costs for many mitigation measures have limited basis in the open literature. Costs are therefore estimated relative to those for the implementation of Required Navigation Performance (RNP) which are available from a number of sources, as described below.

Surface Congestion Management

Every airport has a limit to the number of aircraft it can efficiently handle as a function of runway configuration, weather conditions, etc. Surface congestion management techniques aim to constrain the number of aircraft taxiing on the surface during periods of high demand. "Excess" flights are held at the gate or some other appropriate location with engines off until they can be released to the departure runway more efficiently. As a result, "engines-on" taxi-out time, fuel burn and emissions can be reduced. We use taxi fuel-saving estimates of 15% from an extensive US-wide analysis[33] averaged over all operations at the top 35 airports. The related airline costs are expected to be relatively low and set at 10% of the corresponding RNP costs. By contrast, air traffic control (ATC) equipage and training costs are expected to be more significant due to the potential need for new equipment and procedures in the tower, so these costs were set at 50% of the corresponding RNP costs.

Single Engine Taxi

Single-engine taxi operations involve taxiing aircraft running less than their full complement of engines, i.e., a single engine in the case of twin-engine aircraft. Savings are lower than 50% because of the higher thrust required from the running engine, and the extra fuel needed for cross-bleed starts. According to a survey of pilots, single-engine taxiing would result in a 37% taxi fuel burn reduction, on average.[34] The application potential is estimated to be around 50% due to perceived problems associated with the procedure, which reduces its use in practice. (These include excessive thrust on the operating engine, maneuverability issues, problems starting the second engine, and distractions and workload issues). This measure comes at zero extra cost to ATC unless engine start problems become a cause for major surface inefficiency. Airlines incur no equipage costs, but may incur a low crew training cost, so the cost estimates are set at 20% of the corresponding RNP costs with a zero cost minimum to reflect potential offset due to cost savings from reduced engine maintenance.

Optimized Departures Procedures

Departure requires high thrust levels for take-off and climb when the aircraft is at its highest weight, and as such the fraction of fuel burn in this phase is high relative to its duration. A number of operational options apply, including RNP/RNAV (Area Navigation) departures coupled to optimal climb profiles. These enable aircraft to fly more precise and flexible departure trajectories, potentially including fuel-optimized profiles, using advanced guidance and navigation technologies. However, these can require significant airspace redesign effort and modern aircraft equipage. They are therefore likely to be implemented primarily at the busiest airports, resulting in an estimated application potential of 75%. While take-off and climb fuel-saving benefits of 20% are based on estimates provided by *ref 35*, airline crew training costs, and airline equipage costs are estimated to average $125,000 and $300,000 per aircraft, respectively, based on results from *refs 36 and 37*. ATC training costs are assumed to be similar to airline crew training costs. ATC equipage and procedure design costs are assumed at $1 million but one-off per airport.

Lateral/Vertical/Speed Inefficiency Reduction during Cruise

Cruise typically accounts for the largest fraction of fuel burn and hence provides opportunities for meaningful operational fuel savings. Inefficiencies exist in the lateral, vertical and speed domains. In the lateral domain, the en-route flight environment consists of a network of airways that simplify management of traffic flows but often extend the flight route well beyond the shortest direct route. Greater use of more direct routes by giving aircraft more navigation authority would reduce lateral inefficiency (i.e., excess ground track distance), and therefore fuel burn and emissions. In the vertical domain, most domestic flights are currently flown at a single cruise altitude to minimize pilot and controller workload. Recent analysis suggests that step climbs have fuel-savings nearly identical to those of the more optimal cruise climbs, while being compatible with existing ATC procedures.[38] In the speed domain, airlines often fly faster than their fuel-optimal speeds (e.g. to maintain schedule), while ATC often assigns aircraft common speeds that are not optimal to aid in traffic flow management. Significant fuel burn and emissions could be saved by allowing greater use of optimized speed profiles when operationally feasible to do so. Cruise fuel burn benefits of 5.5% are based on literature values.[39,40,41] Due to limitations such as airspace complexity and volume, an applicability potential of 75% is assumed. Costs are likely to include modified airline flight planning and training costs and ATC equipage and training costs. These are estimated to be 20% of the corresponding RNP costs.

Optimized Approach Procedures

The descent and approach phases of flight typically involve lower fuel burn than other phases of flight as the engines are at lower thrust, unless inefficient holding patterns are required for extended periods of time. Still, there are meaningful fuel burn reductions that can be achieved through the use of strategies such as RNP/RNAV approach procedures (as described above), Continuous Descent Approaches (CDAs) and Delayed Deceleration Approaches (DDAs). CDAs are designed to eliminate level segments in conventional "step down" approaches, keeping aircraft at higher altitude and lower thrust for longer, thereby reducing noise impacts as well as fuel burn and emissions. DDAs involve optimizing the speed profile so that aircraft remain in clean/low drag aerodynamic configurations for longer, with associated fuel reductions. Various Optimized Profile Descents (OPDs) are being explored which can incorporate RNAV/RNP lateral, CDA vertical and DDA speed profiles from top of descent to the final approach. Descent and approach fuel burn benefits of 40% are based on *refs 36,42,43*. Application potential and costs are assumed identical to those for optimized departure procedures.

Airline Operational Strategies

The airline operational strategies for reducing fuel burn and emissions described below consist of seven measures. In each case, the key figures of our estimates are summarized in Table 3, along with figures from the literature.

Reducing Contingency Fuel

Contingency fuel is added in addition to taxi, trip and reserve fuel at the discretion of the airline dispatcher and pilot. This allows for unforeseen airborne delays and increased airborne holding, thus mitigating the risk of diversions. Because of the high costs associated with diversions, contingency fuel is typically increased beyond the minimum required, which increases aircraft weight and fuel burn. Thus, when attempting to reduce contingency fuel, airlines must balance the cost reduction with the increasing risk of diversions.[44,45] Unfortunately, data from the publicly accessible literature does not allow the amount of contingency fuel to be related to the probability of flight diversions. Based on estimates by *refs 46,47*, we thus assume a 300 kg reduction of contingency fuel at zero additional costs while maintaining schedule reliability and safety. Using the aircraft performance model derived rule of thumb that 1,000 kg weight savings would reduce narrow body aircraft fuel use by around 1.25%, a reduction of 300 kg would result in annual block fuel savings of 0.38% or 11,000 gallons per aircraft, which translates into fuel cost savings of $32,800 per year at the 2012 fuel price of $3.1 per gallon.

Early Aircraft Replacements

The average fuel burn of commercial aircraft increases by about 0.2% per year of age.[48] At the same time, as a rule of thumb, fuel burn of *new* aircraft declines by around 1% per year.[49] To exploit the benefit of reduced energy use of new aircraft, existing aircraft could be retired (we assume scrapped) before the end of their useful life. The fuel-savings potential and costs of early replacement depend on the fleet age structure and the fuel burn improvement offered by the replacement technology. (When calculating the costs of early replacement, for simplicity, we only take into account the capital costs of the new aircraft and the difference in fuel burn compared to the old aircraft it replaces). If substituting Intermediate Generation Aircraft for vehicles older than 25 years in 2020, the average fuel burn reduction would be 52% on an aircraft basis. Because as much as 11% of the fleet would be affected, the fleet-based decline in energy intensity would be nearly 9%.

Increased Passenger Load Factor Through Reduced Flight Frequency

Between 2000 and 2012, the number of major airlines serving the vast majority of the US passenger market declined from 10 to only 5, thus allowing costs to be cut through a number of options, including the reduction of previously competing flights.[50] This flight frequency reduction has led to an increase in passenger load factors and a decrease in energy intensity. Further flight frequency reductions and thus increases in passenger load factors seem possible, especially since several US network carriers already experience load factors of 85% or above.[51] We explore a 2% increase in the 2012 passenger load factor relative to the 2012 level of 84%, which has two opposite effects on fleet fuel burn, i.e., an increase by some 0.3% because of the higher passenger load, and a decline by 2% due to the reduced number of flights. Because a reduction of flight frequency requires a smaller fleet, phasing out older aircraft generates an additional fuel efficiency benefit. The net change in direct operating costs (DOCs) results from increased passenger re-accommodation expenses in the event of flight delays and cancellations[52,53], lost revenue due to a lower number of passengers resulting from the reduced flight frequency relative to not implementing the measure[54], higher fuel costs per flight due to the larger number of passengers on board, and lower total DOC from the reduced number of flights operated. (Another element is an opportunity cost, resulting from the higher number of spilled passengers who can't purchase tickets on their desired flights because they are fully booked. Before the use of modern revenue management, these costs would have represented approximately 75% of the average airfare as used by the Boeing Spill Model.[55] However, with the introduction of modern revenue management and "junk" fares, spilled customers are typically willing to pay significantly less than those passengers not spilled. We therefore assume, while increased load factors do lead to an increase in the percentage of passengers spilled, the cost associated with this increased spill to be negligible). Because the fleet fuel burn reduction term dominates, the strategy would lead to a net DOC reduction of $280 million for the US narrow body fleet under 2015 conditions.

Increased Passenger Load Factor by Better Matching of Aircraft Type to Mission

Airlines typically attempt to minimize the number of aircraft types in their fleet to increase commonality, reducing crew training and maintenance costs, and improving flexibility. However, this practice also leads to the use of larger and longer-range aircraft than required for many flight segments, thus increasing fuel burn. We examine enhanced matching of aircraft type to mission by tailoring the size of aircraft to the missions flown. Thus, smaller aircraft types (regional jets or turboprops) could replace narrow body aircraft on markets with suitable stage length and sufficiently low load factor on a one-to-one basis. This strategy would lead to fuel burn reductions of 33% and 57% for regional jets and turboprops respectively, but at the cost of reduced fleet flexibility, higher maintenance and crew training expenses, higher non-fuel costs generally due to lower block speeds, and higher passenger re-accommodation costs associated with the resulting increase in passenger load factor. Regional jets could replace 0.4% of all narrow body aircraft related RPK in 2012, which would cause a net increase in total DOC by $2.1 billion. In contrast, turboprops could replace 0.3% of narrow body aircraft related RPK in 2015, while an increase in total DOC of $2.5 billion could be expected.

Reduced Fuel Tankering

Because fuel prices differ across airports, airlines sometimes take a sufficiently large amount of fuel on board at an airport with lower fuel prices to cover both legs of a return trip, as long as the maximum landing weight is not exceeded. All other factors being equal, such fuel tankering is profitable when the cost associated with carrying the extra fuel is lower than the difference in fuel costs between the two legs when refueling at the airport with higher prices. Based on interview-based data from *ref 56*, we assume that 15% of all passenger aircraft flights tankered fuel in 2012, experiencing average net cost savings of $210 per flight. Accordingly, we estimate that eliminating tankering would result in a fuel burn reduction of 0.26% per flight, at a cost of $210 per flight at 2012 fuel prices of $3.1 per gallon.

Additional Engine Wash

The air ingested by aero engines is typically contaminated with small particles of sand, salts, chemicals, and unburned hydrocarbons, which deposit on surfaces inside the engine compressor and core, thus increasing fuel burn. Increasing the frequency of engine washing reduces the accumulation of internal dirt, hence reducing fuel burn deterioration. A range of engine wash services have become available that can be carried out overnight at an airport stand, including EcoPower[57] and Cyclean by Lufthansa Technik[58]. Based on estimated benefits from *refs 58, 59*, and a review of airline environmental reports, we estimate that the marginal benefit of doubling the frequency of engine washing from one per aircraft per year may reduce fuel burn by 0.25%, or $22,000 per aircraft at $3.1 per gallon. We assume engine wash costs of $4,600 per engine[60].

Surface Polish and Reduced Decorative Paint

In addition to protective paint that prevents corrosion of metals and erosion of and moisture ingress into composite materials, nearly all aircraft use decorative paint. The decorative paint of a fully painted Boeing B737-700 weighs about 81 kg.[61] Removing that amount of paint with the exception of airline markings would result in a 70 kg lighter aircraft, which translates into a nearly 0.1% fuel burn reduction, but requires surface polishing. We apply this measure to only 10% of the fleet because of marketing considerations and the increasing share of composite materials that require protective and thus decorative paint. Using the 2012 fuel price of $3.1 per gallon, a nearly 0.1% block fuel burn reduction of narrow body aircraft would result in fuel savings of around $8,000 per aircraft per year (using the numbers from Table S1). However, the higher costs of washing and polishing result in up to $120,000 per aircraft per year.[61]

Interaction of Measures

Several of the 21 measures examined in this study interact. For example, early-replaced aircraft may not need to be retrofitted. Similarly, an increase in passenger load factors due to reduced flight frequency requires a smaller fleet. The reduction of fleet size can be materialized through retiring the oldest aircraft (assumed here) or through introducing a smaller number of new aircraft. When retiring the oldest aircraft, this measure interacts with the early aircraft replacement strategy, as both measures change the fleet's age distribution beyond the annual turnover. We resolved this interaction by modifying the fleet composition in relation to each of these two measures. The new fleet composition is then the basis for all other measures.

In addition, not all of the measures within Tables 1-3 can be introduced simultaneously. Some options are mutually exclusive, such as evolutionary aircraft designs, open rotor engine aircraft, and engine retrofits. In addition, strategies can interact across the family of measures in Tables 1-3. For example, airlines need to make a choice between electric taxiing systems and single engine taxiing. Similarly, surface congestion management procedures reduce the amount of taxi time and thus the fuel-savings potential provided by single engine taxiing and electric taxiing systems. We dealt with these conflicts by ensuring that the additive application potential of the overlapping alternatives is less than or equal to 100%. Clearly, this is only a necessary condition for reducing the interaction of measures—careful choice of user inputs is required for their minimization.

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