LSE

SKY HIGH ECONOMICS

Chapter Two: Evaluating the Economic Benefits of Connected Airline Operations

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In association with inmarsat aviation

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Foreword

It is my pleasure to introduce to you the second chapter of *Sky High Economics: Evaluating the Economic Benefits of Connected Airline Operations.*

Conducted by the London School of Economics and Political Science, the *Sky High Economics* study is the first of its kind to comprehensively model the economic impact of inflight connectivity on the aviation industry. Following the first instalment, *Quantifying the Commercial Opportunities of Passenger Connectivity for the Global Airline Industry,* which focused on revenue potential, this report shines new light on the cost benefits of inflight connectivity. Specifically, how secure, high-quality connectivity services can also deliver powerful commercial efficiencies for airline operations, with resulting advantages for safety and environmental impact. It demonstrates multi-tiered benefits across fuel consumption and CO_2 emissions, aircraft performance and maintenance, risk mitigation, on-time arrivals and departures, airspace management and improved fleet utilisation.

This second chapter is close to our heart, as Inmarsat is the leading provider of reliable satellite communications to the cockpits of the world's airlines. Over 90% of all transoceanic aircraft have depended for 25 years on our communications for their safety. Now, advances in bandwidth and the rapid emergence of an ecosystem of supporting applications are transforming safety and operations services into a strategic asset, with enormous consequences for the future of the industry.

Today, we're working with a growing list of airlines that are adopting connectivity across the entire aircraft, from cabin to cockpit. In recent years, we have invested in new networks allowing us to become the only aviation connectivity provider with the infrastructure and the experience spanning both domains. We're helping airlines realise new revenue streams and achieve striking operational efficiencies, while managing the secure segregation of passenger and mission-critical safety data. The launch, earlier this year, of Inmarsat's SB-S service brings high-speed, multi-channel connectivity to the flight crew for the first time. In layman's terms, this means that the aircraft opens up and becomes an integral part of an airline's IT network, enabling new capabilities, from visual real-time weather to inflight aircraft health and performance monitoring. Perhaps most importantly, it represents a crucial step towards the digitalisation of air traffic management, ushering in improvements in communication, navigation and surveillance that are essential if the industry is to meet the demands of growing passenger traffic worldwide.

The findings of this research highlight the benefits early adopters are already seeing, and point to many further opportunities soon to come. The complete connected aircraft will be pivotal to the digital transformation of the airline industry.

We are proud to play a part in this revolution and excited by what lies ahead.

Bring It On!

Executive Summary

This is a moment of great change in the aviation industry. Digital transformation, so characteristic of terrestrial markets over the past decade, is taking to the skies. At the heart of this revolution is the connected aircraft.

The connected aircraft, facilitated by satellite communications and integrated with the Internet of Things (IoT), is enabling a wide range of efficiencies and enhancements across fuel consumption and emissions, maintenance, flight optimisation, fleet utilisation, airspace capacity and safety. **Together, these operational benefits could yield savings for the global airline industry of between US$5.5 billion–US$7.5 billion annually based on existing connected aircraft numbers, rising to between US$11.1 billion–US$14.9 billion by 2035. A 0.75–1.00% reduction in the IATA consolidated US$764 billion annual global airline cost of operation.**

Today, the airline industry is experiencing a period of exceptional growth, but the forecast doubling of air traffic by 2035 will require a more efficient use of assets to reduce fuel and CO_2 emissions, and increase capacity while assuring safety. Without a reassessment of technology and infrastructure, it is uncertain how the industry, and the finite airspace it relies on, will accommodate the predicted growth. Expert interviews indicate the consolidated annual benefit of operational connectivity could be a saving of around 2.5%–5.0% of current fuel consumption, with an associated fall in emissions. Satcom-enabled air traffic management initiatives offer the potential to reduce separation minima, counteract congestion and manage more aircraft more safely and efficiently. The IP-connected aircraft promises more than just commercial advantage; it is increasingly an operational necessity.

To enable these efficiencies, a new generation of secure, high-bandwidth satellite communication services is emerging, connecting an array of specialist applications with IoT, cloud, artificial intelligence and big data capabilities. This integrated digital ecosystem can facilitate gigabits of data transmitted to and from connected aircraft today, and terabytes in the future. It's been estimated that over the past 15 years, satellite communications have resulted in savings for the global airline industry of over US$3 billion. These new services have the potential to rapidly dwarf this figure.

Drawing on primary research and secondary data, including industry interviews with airline managers; regulatory agencies; service providers and third parties; subject matter experts; developers and suppliers of aircraft equipment and software solutions and others, this study explores the benefits of the connected aircraft across four principal categories:

- Connected Operations Services
- Maintenance Operations Control Services
- Airline Operations Control Services
- Air Traffic Control Services

Connected Operations Services

The connected aircraft presents numerous opportunities to transform often complex and poorly optimised airline operations processes, from gate-to-gate. Satcom connectivity can deliver both efficiency and safety improvements across pre- and post-flight reporting, flight planning and logistics, and flight optimisation, reducing the potential for delays, costs and passenger frustration.

By integrating real-time aircraft data with their Operations Control Centre and customer relationship management databases, airlines can create live dashboards for tracking, monitoring and distributing information on the ground. Linking an automated catering solution with reservations and departure control systems can enable dynamic adjustments to on-board inventory, saving weight and reducing costs by an estimated 7% per flight. Consistent access to winds uplink data can allow for more accurate contingency fuel planning that could result in annual savings of around 850 million litres industry-wide, and a reduction of two million tonnes of CO_2. Real-time flight data used to improve the reliability of arrival time prediction could reduce crew-related delays by 33% or more, yielding savings in the region of US$1.2 billion a year.

Maintenance Operations Control Services

Modern long-haul aircraft can generate up to 500GB of data per flight and each new generation of aircraft is forecast to create around 30 times more data than the older generation it replaces. This data can reveal insights into aircraft systems and performance with the potential to revolutionise maintenance processes.

Connected aircraft can transmit data to secure cloud services or ground-based servers for monitoring and big data analytics. This allows airline operations teams to pinpoint faults before they become major problems, and use the information to make informed decisions that can reduce costly unscheduled Aircraft on Ground (AOG). With the advent of predictive modelling, parts can be replaced that are identified as targets for replacement before they fail, during scheduled maintenance windows. This can reduce costs, enhance safety, and innovate service delivery through third-party management of critical components.

Interviews and analysis of current AOG costs and contributing factors reveal a broad variation in expected benefits across different airlines. Predicted AOG reductions could result in global savings of US$3 billion to as high as US$46 billion annually.

Airline Operations Control Services

Inflight connectivity offers a wide variety of benefits for Airline Operations Control, from flight and cabin crew efficiencies to flight optimisation and disruption management.

The connected aircraft redefines how flight and cabin crews work and communicate. Crew briefings can be delivered directly to devices on the aircraft, including information currently provided manually at the gate. Traditional pilots' flight bags can be replaced by connected Electronic Flight Bags (EFBs), saving weight and enhancing productivity with in-air updates. A continuous, secure data exchange can occur between the ground and the aircraft with real-time telemetry, tracking, and flight data streaming, including Black Box in the Cloud™ features.

Live weather and environment updates streamed to EFBs improve situational awareness and support decision-making. Pilots can avoid areas of severe weather with greater confidence and precision, yielding fuel savings, improved safety and lower CO_2 emissions. Speed and other parameters influencing the Cost Index calculations for fuel performance can be optimised. These enhancements, in turn, facilitate dynamic routing. Industry discussions and trial results indicate estimated annual savings from improved navigation and adverse weather avoidance could deliver annual cost savings of US$1.3 billion globally per year.

The benefits of avoiding turbulence could be even higher, yielding an estimated range of annual global fuel savings of US$1.3 billion-US$2.6 billion, further savings in the range of US$409 million-US$806 million annually for airframe inspections and follow-on repairs, as well as a potential 98% reduction in unnecessary airframe inspections, saving US$44.7 million.

Airlines are also seeking to leverage connectivity to enhance their telemedicine capability and reduce preventable diversions. If emergency diversions were reduced through connected telemedicine, the benefits could be significant: a reduction of 25%-50% from current annual global diversion totals could result in a cumulative saving of between US$3.7 billion and US$7 billion respectively between 2018-2035.

Over time, the emergence of fly-by-wire technologies could eventually result in the pilotless aircraft. Given cultural barriers, this is likely to occur in stages. The global cost saving attributed to pilotless aircraft has been estimated to reach US$35 billion by 2040, achieved initially through a reduction of one crew member in the medium term, yielding an estimated US$21 billion in annual savings,.

Air Traffic Control Services

The connected aircraft is a catalyst in the transformation of the aviation ecosystem. IP-enabled real-time data exchanges can reduce separation distances between aircraft in the sky, allowing airspace and existing airport and air traffic control infrastructure to accommodate increasing passenger and aircraft numbers. The benefits of satellite-based navigation, automating aircraft position reporting and providing digital communications, are estimated to be worth an annual saving of US$3 billion.

The efficient use of airspace is a long-term aviation goal. Aircraft fuel accounts for around 18%–20% of airline operating costs and one third of total expenses in the global airline industry. Furthermore, the environmental impact of failing to make air transport efficiencies could be high. Engine technology improvements have enhanced fuel efficiency, but the gains achieved can be rapidly offset by flying inefficient routes. The ultimate fuel reduction that an aircraft can achieve is also impacted by congestion, which is managed by air traffic control outside of the airline's remit. Industry interviews and analysis of secondary data indicate that IP-based flight deck communications could bring about a 1%–2% reduction in current global fuel consumption, resulting in savings of US$1.3 billion, 3.39 billion litres of fuel and 8.5 million tonnes of CO_2 annually.

Flight separation is an area of considerable activity and focus for regulators and airlines. 4D trajectory management initiatives and enhanced digital capabilities enabled via satcom, offer the potential to reduce separation minima, lowering fuel use, emissions and enhancing safety, while permitting more controlled arrival times, and increasing airport throughput. This is a key requirement in the industry's challenge to meet growing passenger numbers without incurring additional delays, fuel burn and CO_2 emissions, or resulting in additional infrastructure costs, such as new airport construction.

Until recently, the business case for connectivity has been largely based on incremental revenue alone. But a growing number of airlines are now taking into account a broader context that includes both operational savings and ancillary gains. These two areas are not mutually exclusive. They are both part of the wider, end-to-end digital transformation occurring across the industry, starting from initial contact with the passenger and extending well beyond the aircraft's arrival at the destination gate.

This research highlights a diverse range of benefits of connected operations. These include economies in fuel consumption, a reduction in delays and improved on-time departures, innovations in maintenance processes, fleet utilisation efficiencies, safety enhancements and others. Together, these are forecast to yield annual savings of up to US$14.9 billion globally by 2035.

The forecast increase in aircraft traffic will create both challenges and opportunities. The IP-enabled aircraft is an integral step towards addressing the issues while facilitating efficiencies and benefits. Without it, the industry may be constrained by the limitations of finite airspace and a growing environmental agenda.

Dr Alexander Grous Biography

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Dr Alexander Grous has been engaged at the LSE since 2005, and works across the Department of Management and the Department of Media and Communications at the LSE in a combined teaching and research role in the areas of Innovation, Socio-Economics, Communication Technology and Transport Economics, amongst other areas. Dr Grous is also Director of the Research Function in LSE Enterprise, engaged across multiple projects for clients. He brings considerable commercial experience to the LSE from previous roles at CXO level in mobile communications (including satellite), high-technology, FMCG, e-commerce, Banking and Finance.

Dr Grous specialises in the quantification of socio-economic value encompassing both a social and economic impact at the company, regional or national level, or wider. His extensive work in these areas has resulted in high profile reports and media coverage including the impact of cycling to the UK economy, business and health; the socioeconomic impact of mission critical broadband to the UK and the EU; the productivity enhancing impact of communications in the UK; and recent extensive socio-economic work for FTSE 100 firms that are not public domain including Microsoft, Warner Brothers, Amadeus, GB Group, and others.

Dr Grous' work is often utilised for Policy and Government input, and he engages at this level to facilitate.
Dr Grous also brings considerable experience in telecommunications having held strategy roles in mobile strategy and satellite communications with Telstra (Australia/UK) including engagement over two years with Inmarsat in the UK as Telstra's representative on the Working Group related to the initial development of Inmarsat's mobile satellite service.

He was also MD of Lockheed Martin's Infocom Division for EMEA and CEE/CIS including participating in satellite communication launches and joint ventures for fixed, mobile and broadband in the region, defining the market potential for services across ground and air. Dr Grous maintains transport economics and communication technology as an active area of research and teaching.

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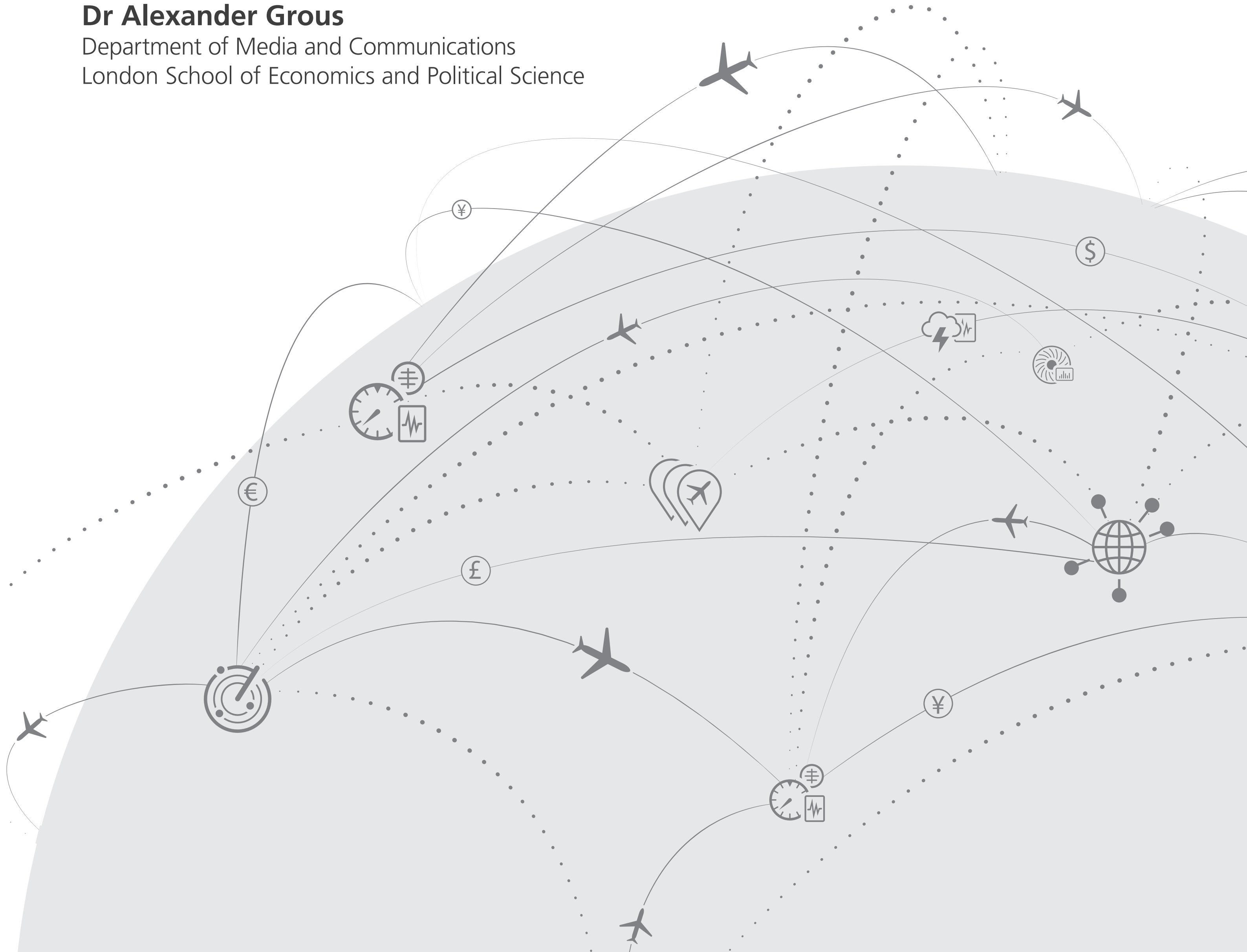

The Connected Aircraft: Transforming Airline Operations

The airline industry is experiencing a period of exceptional growth, with IATA forecasting a doubling of passenger numbers by 2035.[1] Leading aircraft manufacturers are forecasting significant increases in aircraft deliveries over the same period.[2/3] Growth also brings challenges however: continued expansion and intense competition have set new expectations for value, constraining operating margins in the process. Increased traffic also results in additional fuel burn and has an environmental impact.[4] Without a reassessment of technology and infrastructure, the challenge remains how the industry, and the finite airspace it relies on, can accommodate the growth predicted.

This is also a time of significant change in the air transport industry. The digital transformation observed in many terrestrial markets over the past decade is migrating skywards, creating wide-ranging opportunities but requiring closer collaboration and transformation in the aircraft's ecosystem. The rise of the 'connected aircraft', facilitated by satellite communications and integrated with the Internet of Things (IoT), is initiating a data revolution. The aircraft is no longer an isolated unit, but has become an IP-enabled node in a wider digital framework. This new operating environment is bringing increased visibility to the flight crew, ground crews, airline operational control, air traffic management and an emerging network of supporting service providers.

The first chapter of this study, *Quantifying the Commercial Opportunities of Passenger Connectivity for the Global Airline Industry,* explored the economic potential for connected ancillary revenues. The benefits of connectivity are significantly greater than Wi-Fi and associated passenger services in the cabin that create new opportunities for airlines to monetise passengers. Operational connectivity offers the potential to reduce bottom-line operating costs and enhance safety while meeting the needs of growing demand.

The connected aircraft facilitates efficiencies and enhancements encompassing fuel consumption and emissions; maintenance; flight operations; airspace capacity; and safety. Consolidating these advantages could deliver substantial economic, environmental and, ultimately, social benefits, including a reduction in the industry's annual global fuel use and a net reduction in CO_2 output.
The operational benefits could yield savings between US$5.5 billion–US$7.5 billion annually based on existing connected aircraft numbers, rising to between US$11.1 billion–US$14.9 billion by 2035.

Collectively, the potential for multiple savings, efficiencies and safety enhancements could equate to a 0.75–1.00% reduction in the IATA consolidated US$764 billion annual global airline cost of operation.[5]

The Connected Aircraft Ecosystem

This report reviews the potential benefits that can be delivered by the connected aircraft across four principal categories, as shown in Figure 1: *Connected Operations Services, Maintenance Operations Control Services, Airline Operations Control Services and Air Traffic Control Services.*

Figure 1: Connected aircraft ecosystem

- ***Connected Operations Services*** includes sections on *The Airline, The Aircraft and The Airport,* encompassing pre- and post-flight communications and reporting; data impacts on arrival prediction; turnarounds; and delay management. This section also highlights the emerging importance of cybersecurity in a connected digital ecosystem.
- ***Maintenance Operations Control Services*** reviews the impact of real-time performance and aircraft health monitoring on maintenance, repairs and operations (MRO) capabilities. This encompasses the enhanced impact that data can facilitate in just-in-time responsiveness; reducing unscheduled AOG; enabling straight-through supply chain management; and improving airlines' predictive maintenance capabilities.
- ***Airline Operations Control Services*** reviews the potential benefits that could ensue from data flows between the airline operations centre (AOC) and the aircraft, including: *Crew Connectivity; Flight Optimisation* (including live weather and turbulence reporting); *Environmental Factors; Irregular Operations* (including medical diversions); *Disruption Management; Safety and Operations Risk; Situational Awareness;* and the impact of impending *Future Regulations.*
- ***Air Traffic Control Services*** reviews connectivity as an enabler for more efficient airspace management, including current satcom-enabled initiatives to reduce separation minima and support more optimal flight routing that can result in greater fuel efficiency and lower CO_2 emissions.

Enhanced connectivity can facilitate multiple benefits for airline operations, yet many applications are still in their infancy or yet to be fully assessed. These benefits are expected to accrue in an accelerated manner as airline connectivity penetration increases. This study does not endeavour to quantify every benefit, rather it is a preliminary review of the most commercially significant benefits and draws broad conclusions as to their consolidated economic impact.

This report reviews activities in the connected aircraft ecosystem that can result in efficiencies in fuel consumption, CO_2 reductions, operational and infrastructure improvements, and other areas. The analysis utilises primary research and secondary data including industry interviews with airline managers; regulatory agencies; service providers and third parties; subject matter experts; developers; and suppliers of aircraft equipment, software solutions and others.

Forecast Industry Efficiencies

The forecast doubling of air traffic by 2035[6] will increasingly require a more efficient use of assets to reduce fuel and CO_2 emissions, increase capacity and enhance safety. Industry interviews indicate the consolidated annual benefit of operational connectivity could be around 2.5%–5% of current fuel consumption, in addition to savings accruing from other areas including maintenance efficiencies and a reduction in delays. Research indicates that savings could accrue evenly between fuel savings and delays versus other areas.[7] A number of airlines currently trialling operational connectivity are reporting savings within this range.[8] This is also being reported by solutions providers of flight management software and related products that are indicating savings of up to 5% in both fuel and emissions and flight times and delays.[9]

If a lower bound estimate of 2.5% was achieved in the current annual fuel consumption of the airline industry, this could yield US$3.25 billion savings in fuel costs, an annual reduction of 8.5 billion litres, and 21.3 million fewer tonnes of CO_2. If a comparable saving figure was achieved in the reduction of delays, the total annual saving could be approximately US$6.5 billion. This aligns with recent industry research and forecasts for connectivity benefits, predicting a US$5 billion annual saving, divided evenly between fuel savings and delays and other areas.[10] These and the other benefits of a connected aircraft are summarised in Figure 2.

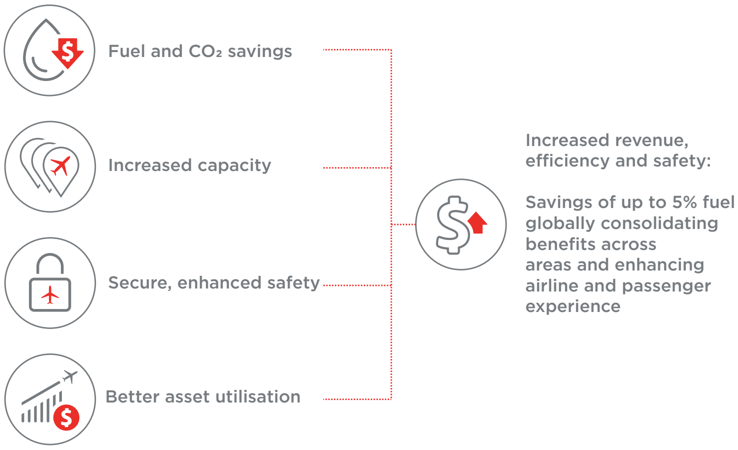

Figure 2: Connected aircraft benefits and research summary
(Source: LSE research using IATA, airline, government and industry data and interviews.)

Next Generation Connectivity Services

The facilitation of enhanced efficiencies is made possible due to the adoption of a new generation of secure, high-bandwidth satellite connectivity. These facilitate the integration of flight operations, air traffic control (ATC), specialist applications within IoT, cloud, artificial intelligence and big data capabilities. This integrated digital ecosystem can facilitate gigabits of data being transmitted to and from connected aircraft today, and terabytes in the future.[11] This functionality will be required as modern aircraft continue to generate an increasing amount of data per flight. Enhanced connectivity will deliver additional information to the cockpit and facilitate inflight data transmission. This is also reflected in developments at airports and in airspace management.

It has been estimated that over the past 15 years, satellite communications have resulted in savings to the global airline industry of over US$3 billion.[11] An IP-connected aircraft has the potential to significently increase these savings.

Connected Operations Services

The potential benefits of satcom-enabled *Connected Operations* have been segmented into four key areas: *The Airline; The Aircraft; Airports; and Airspace.* This section reviews the first three areas, with the benefits potentially accruing to airspace management reviewed in a subsequent section.

Figure 3: Connected Operations Services

These areas highlight three core capabilities of the connected aircraft:

1. Remote, real-time, problem-solving diagnostics;
2. Turning the aircraft into a node or 'sensor' in the IoT;
3. Providing digital communication 'anywhere', including oceanic regions and over continental airspace that provides an enhanced complement to HF radio.

These factors facilitate the integration of live airline data with an airline's Operations Control Centre (OCC) and customer relationship management (CRM) databases for the first time. Information can be utilised to create live flight operations dashboards for tracking, monitoring and distributing information on the ground.

The development of the connected aircraft follows the evolution of other digitalised sectors, such as gaming, where technology, platform and content providers have collaborated and released apps. Early stage 'connected aircraft collaboration' is also occurring in the aviation industry between avionics suppliers, standards organisations, airlines and application developers. This has resulted in the release of devices including the pilot's Electronic Flight Bag (EFB). These devices represent a core interface in the enhancement of airline performance through a connected aircraft.[13]

The Airline

Many airline operations processes are undertaken manually or are not optimised at present due to pressure to meet on-time departures. Limited data do not permit diagnostics that can improve efficiency or minimise delays and cancellations. With demand capacity at major global airports near 100%,[14] enhanced efficiency is critical from gate-to-gate. The connected aircraft has the potential to improve current practices and deliver both efficiency and safety enhancements across pre- and post-flight reporting, flight planning and logistics, and flight optimisation.[15]

Pre- and Post-Flight Reporting

The exchange of information and documentation between the flight crew and the OCC can affect on-time departure. Existing pre- and post-flight reporting processes create complexity, expense and often disrupt departure times. Existing satcom connectivity can enhance these processes, reducing the potential for delay, costs and passenger frustration, with additional bandwidth providing the opportunity for improved benefits.[16]

Flight crews are required to arrive at an airport at a defined pre-flight time to visit the Crew Room and print out flight documentation, that can be at least an hour before departure time. The number of aircraft based at an airport defines the number of crew required, in addition to the operational facilities, including the number of computers, printers and the space allocated to facilities. Additional time is also required by the crew following their initial briefing to travel to the aircraft for pre-flight inspection, with this process often taking 30 minutes or longer. Some airlines limit the number of flight plan changes that can be made once an aircraft has left the gate, forcing a return for re-dispatch if that limit is exceeded.[17] If the pilot or OCC identify a potential issue during pre-flight checks, such as with the Flight Management System (FMS) or another issue, an amendment is re-printed and returned to the aircraft. At the conclusion of every flight, hard copy flight plans are provided to the administrative team for archiving. A delay creates additional issues including crew shifts timing-out, or the amendment of en route alternates and requires Extended-range Twin-engine Operational Performance Standards (ETOPS) changes, with these typically filed two to four hours before a flight.[18]

Currently, VHF radio is utilised for voice communications while the plane is on the ground. VHF also carries text-based instructions via the Aircraft Communications Addressing and Reporting System (ACARS), a digital data link system that transmits short messages between the aircraft and the control team. VHF radio signals only support a very low data rate (300bps in the case of ACARS)[19] and are increasingly subject to saturation. In the pre-flight stage, limited opportunity exists for amendments to critical processes such as de-icing and fuel requests. In the case of de-icing, holdover time confirmation is required. This decision is often made jointly between the pilot and airline operations, with guidance on hold-length often requiring the involvement of a dispatcher.

Where available and when complying with operational procedures, ground-based Wi-Fi or mobile networks such as 4G can facilitate data exchange and streamline these processes. Ground-based connectivity is often unavailable in airports or in areas within an airport. In the absence of adequate ground-based Wi-Fi, satellite-based broadband offers an alternative mode for required communication and reporting that can reduce the reliance on the current manual processes that can contribute to delays.[20] Reliable connectivity can result in optimised ground tracking and efficient queuing, prioritisation and communication, ensuring flights depart on time and minimise fuel burn on the ground.[21] This facilitates re-dispatching without the requirement for the aircraft to return to the gate. In addition, mandatory crew arrival times could be truncated and crew briefings delivered on board the aircraft, reducing the requirement for physical Crew Rooms.

Fuel and Weight Optimisation

A reduction in the weight of an aircraft yields lower fuel consumption and reduced CO_2 emissions, with airlines benefiting from even a small reduction in weight.[22] Air Canada estimated that reducing the weight of each aircraft by 1kg saved 24,500 litres in annual fuel consumption, reducing its costs by US$20,000 and producing 63 tonnes less CO_2.[23] American Airlines estimated that the weight saved by switching an 18kg briefcase to iPads for the flight crew reduced fuel costs by US$1.2 million over a year.[24] Other airlines have reported similar savings.[25]

Contingency Fuel

Around 10% of flights depart without winds uplink in their Flight Management Computer (FMC)[26] due to ground communication issues such as radio congestion in airports, 'black spots' for ACARS on stands and 4G blind spots.[27] This lack of data often results in aircraft carrying contingency fuel and additional weight. Results from connected aircraft trials indicate potential average annual savings of around US$0.4 million–US$0.5 million for a fleet of around 300 aircraft.[28] This could yield an annual industry saving of around US$33 million based on current global aircraft numbers.[29/30] Where wind uplink can be consistently uploaded (via VHF and satellite),[31] airlines are reporting fuel savings of 0.23%–0.25%.[32] This could result in global fuel savings of around 850 million litres annually, and a reduction of two million tonnes of CO_2, with an estimated cost saving of US$325 million.[33]

On-board Inventory

A connected aircraft can integrate an automated catering service solution with the airline's reservations and departure control systems to accurately forecast passenger numbers and update catering requirements including forecasts by cabin class. This enables dynamic, real-time adjustments in on-board inventory, resulting in improved order visibility and more efficient inventory management, saving weight and reducing costs by an estimated 7% per flight.[34]

A wide body aircraft has around 40,000 items loaded before take-off, with on-board inventory weighing around six metric tonnes (from a larger available payload consisting of meals, beverages, toiletry bags, duty-free goods, magazines and more).[35] An accurate alignment of inventory with passenger numbers and preferences could yield a weight reduction of 0.42 metric tonnes for a wide body aircraft, equating to US$261 per flight,[36] and around 0.1 metric tonnes for a narrow body aircraft, equating to US$58.93 per flight.[37] Table 1 consolidates analysis using industry data, interviews and information from aircraft manufacturers on fuel and cost savings related to weight reductions, to estimate potential savings. The analysis utilises current connectivity penetration rates for airlines. Interviews indicate that if an airline has adopted connectivity, readily available benefits such as inventory management are likely to be utilised to varying degrees amongst airlines. As penetration of Wi-Fi continues to increase, it is believed that the rate of utilisation will be higher for connectivity-enabled services as more applications and services are released by third parties and utilised by airlines. Table 1 depicts the forecast benefits that can accrue to airlines utilising current aircraft connectivity penetration rates and the forecast growth of these with almost ubiquitous connectivity penetration by 2035.

Aircraft Type	2018	2019	2020	2021	2022	2023	2024	2025	2026
Narrow body	$27,52,000	$35,027,175	$44,416,244	$55,878,465	$79,776,102	$99,436,924	$117,415,496	$130,190,732	$143,846,430
Wide body	$35,091,706	$44,664,364	$56,636,691	$71,252,566	$101,725,272	$126,795,466	$149,720,567	$166,010,712	$183,423,566
Total	**$62,611,706**	**$79,691,539**	**$101,052,934**	**$127,131,031**	**$181,501,374**	**$226,232,390**	**$267,136,063**	**$296,201,444**	**$327,269,996**
Aircraft Type	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Narrow body	$158,443,878	$174,048,601	$181,194,119	$188,701,594	$196,590,807	$204,882,659	$213,599,232	$222,763,860	$238,517,414
Wide body	$202,037,277	$221,935,400	$231,046,898	$240,619,939	$250,679,748	$261,252,976	$272,367,780	$284,053,915	$304,141,817
Total	**$360,481,155**	**$395,984,001**	**$412,241,017**	**$429,321,533**	**$447,270,555**	**$466,135,634**	**$485,967,011**	**$506,817,775**	**$542,659,232**

Table 1: Weight related annual savings for on-board inventory due to connected aircraft

Through the integration of these components with the connected aircraft, airlines can improve the efficiency of inflight services, and achieve an estimated 10% saving in their catering budget from reduced wastage:[38] meals account for 50%–55% of inflight catering spending, followed by bakery, confectionery and beverages.[39] This could yield savings of US$1.76 billion by 2020 from a US$17.6 billion forecast for the global inflight catering market.[40]

The Aircraft

Approximately two-thirds of airlines are forecast to be operating connected aircraft by 2019.[41] This will embed an increasingly greater number of 'nodes' in the IoT and machine-to-machine (M2M) environments. To date, systems in the airline industry have been fragmented, but the advent of connectivity is fostering a consolidation of the aircraft's ecosystem[42] across a number of areas: fuel and engine monitoring to generate performance and maintenance efficiencies; managing equipment status; monitoring consumables; monitoring the aircraft environment; and surveillance.[43] These areas are explored in greater detail in subsequent sections.

The digital transformation of aircraft extends to the activities of employees both on the tarmac and on-board.[44] Increasingly, engineers are wearing smart glasses during maintenance to transmit images for assessment and real-time feedback.[45] With the advent of inflight connectivity, flight crews can transfer images on board the aircraft for analysis on the ground including for telemedicine: more accurate imaging can enhance diagnosis and reduce the risk of mortality in some cases, in addition to preventing unnecessary diversions.

Cybersecurity

The proliferation of satcom connectivity in the airline industry highlights the requirement to ensure data security is robust. Connected aircraft transmit operationally sensitive data that is also integrated within a wider digital ecosystem. Increased opportunities for cyber threats could ensue as the transmission and volume of data grow over time, mirroring other IP-enabled industries such as e-commerce, online banking, and the automotive sector.[46] Over 90% of airlines are forecast to invest in cybersecurity between 2017–2020, almost doubling over this period.[47] The adoption of cybersecurity in the aviation digital ecosystem will continue to evolve as airlines, satcom operators, and other industry participants engage and address both traditional safety services and emerging areas such as communications and information exchange between the flight crew, the cabin crew and OCC, and by passengers accessing data through personal devices.

Satcom communications provides a more secure mode of data transmission than VHF due to the nature of the transmission and the security protocols utilised.[48] Airlines are increasingly addressing cybersecurity through a number of activities: creating dedicated cybersecurity functions and developing and embedding formal cybersecurity procedures into their operational processes; employing leading threat-protection solutions; maintaining a harmonised device access strategy for flight and cabin crew; and other initiatives. Enhanced network security is also occurring at an enterprise level.[49]

Numerous industry initiatives are occurring to address cybersecurity. ESA's Iris programme for Satellite Communication for Air Traffic Management is designing, developing, and implementing a satellite data link service for European continental airspace with a focus on security, safety and industry standards, encompassing a number of areas:[50]

- The addition of the ATN/IPS communications protocol, defined by the international aviation community as the future communication service layer;
- System architecture;
- Increased security, including identifying additional anticipated threats.

The air transport sector is engaged in addressing cybersecurity with industry-wide effort, including the development of a collaborative framework for creating, delivering and maintaining digital security amongst suppliers, original equipment manufacturers (OEMs) and airlines.[51] Initiatives are addressing the administration of security, including the use of risk-based decision-making and effective lifecycle management processes, to ensure that utilised hardware and software remain current and that protection from threats is effective.[52] These efforts extend to the assessment of on-board digital equipment that permits EFBs to access the aircraft's avionics safely while ensuring that data is not compromised.

The rapid progress of threat protection and data integrity in an aviation industry facilitated by the connected aircraft requires the adoption of common standards and the progress of initiatives to establish a trusted operating environment. Key initiatives include the International Civil Aviation Organisation's (ICAO) INNOVA project and its working group "I" that supports cybersecurity and the development of standards through Radio Technical Commission for Aeronautics (RTCA), the European Organisation for Civil Aviation (EUROCAE) and the Airlines Electronic Engineering Committee (AEEC).[53] These initiatives are reflected in the release of a key standard for the aircraft data interface function, ARINC 834.[54] This encompasses the use of ground-based ICT, cloud and networks; on-board software and data integration; secure cockpit and cabin aircraft communications; apps, systems integration; and support.[55] IATA has also highlighted the requirement for collaboration and government partnerships in the development of adequate cybersecurity.[56] The organisation has developed an *Aviation Cyber Security Toolkit* for airlines, airports, ground handlers and others in the value chain that outlines how to undertake internal analysis of current cyber risks and protect critical components, such as IT infrastructure[57]

The Airport

The potential efficiency and environmental gains from a connected aircraft extend beyond the scope of this report. Interviews and industry discussions highlight three core airport activities that can be optimised through enhanced aircraft connectivity: arrival prediction; flight turnaround; and on-time departure:

Arrival Prediction

Accurate flight data can be used to improve the reliability of arrival time prediction. An early or late arrival can result in a gate being unavailable, increasing the time an aircraft spends on the ground with passengers on board.[58] This creates additional cost, fuel burn, and logistical challenges in the process.[59] Real-time data enabled through connectivity maximises the opportunity to align an early or late flight with a gate and disembark passengers. This also improves the efficiency and mobilisation of support teams servicing the plane, including stairs, tugs, refuelling, baggage handling and on-board inventory, and ATC arrival and hand-off times.

Turnarounds and On-Time Departure

Automating communication exchanges between pilots and the OCC can yield system benefits and facilitate on-time departures. Global flight delays are estimated to cost airlines US$123 billion annually, with airline costs comprising US$41 billion and passenger costs US$82 billion:[60] this does not account for other ripple and multiplier effects that could increase this cost to US$200 million annually.[61] Crew scheduling issues are estimated to account for 3% of all delays, equating to US$3.6 billion.[62] Through enhanced connectivity, real-time information could result in adjustments to operational schedules, alternate crews and other activities that could reduce this cost. A reduction of 33% and 66% in crew-related delays would yield savings of US$1.2 billion and US$2.4 billion annually respectively. Interviews with airline managers indicate that they are targeting this area for significant gains with a crew lateness reduction of at least 50% highlighted by many.

Maintenance Operations Control Services

The advent of the connected aircraft can result in benefits to Maintenance Operations Control across a number of areas: *Maintenance Repair and Operations* efficiencies, *Aircraft Health Monitoring,* more efficient *Aircraft Data Loading* and the emerging field of *Predictive Maintenance.* These are depicted in Figure 4:

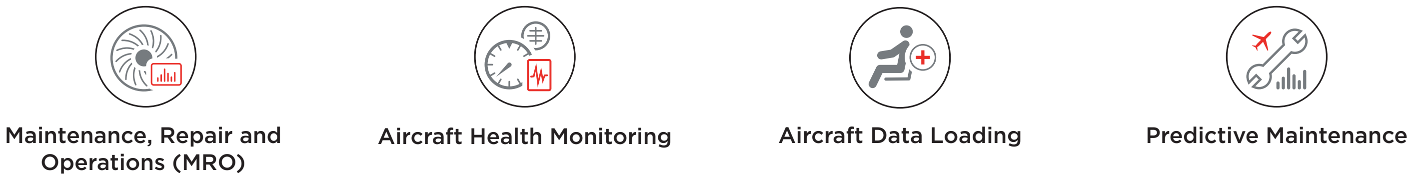

Figure 4: Connected Maintenance Operations Control Services

Connected aircraft can transmit data from on-board servers to secure cloud services or ground servers for monitoring and big data analytics.[63] This provides critical information on aircraft systems and performance that can be reviewed remotely. Data can be streamed in real-time; polled from the ground when required, or triggered by an on-board algorithm. This information can facilitate predictive maintenance; provide inflight maintenance analysis by engineering teams on the ground; and provide support for the flight crew in making key decisions including diversion decisions, avoiding unnecessary deviations and limiting at-gate delays.

Maintenance, Repair and Operations

Interviews with airline managers highlight that preventative activities are a high priority. Maintenance accounts for 10% of an airline's operating costs, with unscheduled maintenance accounting for approximately half of an airline's delays.[64] The hourly cost of a delay is dependent on the aircraft type, airport and other factors.[65] Globally, airlines spent US$62.1 billion in MRO costs in 2016, an amount estimated to grow to US$90 billion by 2024.[66] Engine costs comprise 40% of this, followed by components (22%), base (21%) and line (17%) repairs.

Line Maintenance

Responsive, just-in-time line maintenance will become increasingly important with the rise of connected aircraft. On-board failure of galley equipment, toilets and other loaded items can impact passenger experience, lead to lost ancillary revenue, prompt passenger compensation claims and damage an airline's reputation. A fault with a revenue-generating aircraft item, such as a galley or cart, can potentially affect a flight's ancillary revenue and profitability.[67] Ancillary revenue contributes between 22%–46% of an airline's margin for the world's top 10 airlines, with an average rate of 22% in 2017.[68] A total of US$82 billion is spent annually by passengers on ancillary revenue,[69] with items such as food, seating and duty free accounting for 21% of this total.[70] With a connected aircraft, faults can be reported in real-time electronically, resulting in the preparation of parts and required tools by maintenance teams while the aircraft is between flights. Live MRO system updates that are integrated with the supply chain can also facilitate preventive maintenance, efficiency and safety.[71] This enables greater visibility of line replaceable units (LRUs), just-in-time facilitation, and an optimised journey from warehouse to aircraft. Around 75% of airline managers interviewed indicated that logistical integration was of critical importance to line repairs and in ensuring on-time departures.

Real-time remote diagnostics is possible through two modes: (1) automated, with sensors and/or wireless apps transmitting data to the OCC; or (2) manual, where the flight crew utilise on-board reporting that 'pushes' data directly to the OCC.[72] Interviews indicate that both options can alert the OCC to an issue with a specific aircraft component, including the part number and profile. Data can subsequently be fed into MRO software or an enterprise resource planner (ERP) to schedule parts via the engineers' work schedules, reducing potential down-time. In a straight-through processing model the OCC can further integrate with a supplier, with activities including defect recognition through to the dispatch of parts, and the automated receipt from an airline's MRO system. This capability can maintain on-time departures and minimise the loss of revenue generation.[73] Interviews indicate that remote monitoring provides enhanced benefits for parts critical to aircraft performance such as LRUs encompassing starters, fuel and hydraulic pumps, actuators, sensors, valves and tubing. One Gulf carrier is currently trialling 3D printing of spares at line stations. When the system receives a cabin defect report from an aircraft inflight, the maintenance team can identify the faulty part, print it, and despatch it for installation when the aircraft lands.

Unscheduled Maintenance

Unscheduled aircraft maintenance represents a significant cost for airlines. Table 2 depicts global unscheduled maintenance by aircraft size. Narrow body and small regional jets account for the highest proportion of unscheduled maintenance, followed by large regional jets and wide body jets.

Unscheduled Maintenance	Small Regional Jets	Large Regional Jets	Narrow Body Jets	Wide Body Jets
Proportion of total	37.1%	17.4%	33.1%	4.2%
Cancelled due to maintenance	0.4%	0.8%	0.1%	0.3%
Delayed due to maintenance	4.1%	3.8%	3.6%	5.6%

Table 2: Unscheduled maintenance by aircraft segment and cause: 2016
(Source: http://www.worldtek.com[74`])

The impact of unscheduled maintenance on delays and cancellations can be significant, accounting for 3.06%–4.76% of delays and 0.085%–0.68% of cancelled flights.[75] Unscheduled maintenance can occur due to a number of factors: the malfunction of a part, component or engine; en route events such as bird strikes; lightning damage; ground collisions; and others. Table 3 depicts the estimated global costs for unscheduled maintenance on delays and cancellations in 2017, 2025 and 2035 if no additional intervention measures occur in the industry to reduce this.

Unscheduled Maintenance	Small Regional Jets	Large Regional Jets	Narrow Body Jets	Wide Body Jets
Cancelled due to maintenance	$248,226,120	$496,452,240	$62,056,530	$186,169,590
Delayed due to maintenance	$4,670,728,200	$4,328,967,600	$4,101,127,200	$6,379,531,200
Total 2017	**$4,918,954,320**	**$4,825,419,840**	**$4,163,183,730**	**$6,565,700,790**

Unscheduled Maintenance	Small Regional Jets	Large Regional Jets	Narrow Body Jets	Wide Body Jets
Cancelled due to maintenance	$344,976,277	$689,952,553	$86,244,069	$258,732,208
Delayed due to maintenance	$6,491,220,280	$6,016,252,942	$5,699,608,050	$8,866,056,967
Total 2025	**$6,836,196,556**	**$6,706,205,496**	**$5,785,852,120**	**$9,124,789,175**

Unscheduled Maintenance	Small Regional Jets	Large Regional Jets	Narrow Body Jets	Wide Body Jets
Cancelled due to maintenance	$496,452,240	$992,904,480	$124,113,060	$372,339,180
Delayed due to maintenance	$9,341,456,400	$8,657,935,200	$8,202,254,400	$12,759,062,400
Total 2035	**$9,837,908,640**	**$9,650,839,680**	**$8,326,367,460**	**$13,131,401,580**

Table 3: Estimated annual global costs from unscheduled maintenance by cause: 2017, 2025, 2035

Table 4 depicts the potential cost reductions in 2025 and 2035 that connected aircraft could facilitate. These indicate a potential savings range from 5%–50% with airline managers highlighting that the growth in connected aircraft numbers can result in greater savings over time, with the rate of savings dependent on multiple factors. A lower-bound 5% reduction in unscheduled maintenance was identified for early stage benefits, rising over time. For wide body jets, this could result in a total cost reduction of US$456 million annually in 2025, increasing to US$656 million in 2035.

Unscheduled Maintenance 2025	Reduction	Small Regional Jets	Large Regional Jets	Narrow Body Jets	Wide Body Jets
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	5%	$327,727,463 ***$17,248,814*** $6,166,659,266 ***$324,561,014***	$655,454,926 ***$34,497,628*** $5,715,440,295 ***$300,812,647***	$81,931,866 ***$4,312,203*** $5,414,627,648 ***$284,980,403***	$245,795,597 ***$12,936,610*** $8,422,754,119 ***$443,302,848***
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	25%	$258,732,208 ***$86,244,069*** $4,868,415,210 ***$1,622,805,070***	$517,464,415 ***$172,488,138*** $4,512,189,707 ***$1,504,063,236***	$64,683,052 ***$21,561,017*** $4,274,706,038 ***$1,424,902,013***	$194,049,156 ***$64,683,052*** $6,649,542,726 ***$2,216,514,242***
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	33%	$231,134,105 ***$113,842,171*** $4,349,117,587 ***$2,142,102,692***	$462,268,211 ***$227,684,343*** $4,030,889,471 ***$1,985,363,471***	$57,783,526 ***$28,460,543*** $3,818,737,394 ***$1,880,870,657***	$173,350,579 ***$85,381,628*** $5,940,258,168 ***$2,925,798,799***
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	50%	$172,488,138 ***$172,488,138*** $3,245,610,140 ***$3,245,610,140***	$344,976,277 ***$344,976,277*** $3,008,126,471 ***$3,008,126,471***	$43,122,035 ***$43,122,035*** $2,849,804,025 ***$2,849,804,025***	$129,366,104 ***$129,366,104*** $4,433,028,484 ***$4,433,028,484***

Unscheduled Maintenance 2035	Reduction	Small Regional Jets	Large Regional Jets	Narrow Body Jets	Wide Body Jets
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	5%	$471,629,628 ***$24,822,612*** $8,874,383,580 ***$467,072,820***	$943,259,256 ***$49,645,224*** $8,225,038,440 ***$432,896,760***	$117,907,407 ***$6,205,653*** $7,792,141,680 ***$410,112,720***	$353,722,221 ***$18,616,959*** $12,121,109,280 ***$637,953,120***
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	25%	$372,339,180 ***$124,113,060*** $7,006,092,300 ***$2,335,364,100***	$744,678,360 ***$248,226,120*** $6,493,451,400 ***$2,164,483,800***	$93,084,795 ***$31,028,265*** $6,151,690,800 ***$2,050,563,600***	$279,254,385 ***$93,084,795*** $9,569,296,800 ***$3,189,765,600***
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	33%	$332,623,001 ***$163,829,239*** $6,258,775,788 ***$3,082,680,612***	$665,246,002 ***$327,658,478*** $5,800,816,584 ***$2,857,118,616***	$83,155,750 ***$40,957,310*** $5,495,510,448 ***$2,706,743,952***	$249,467,251 ***$122,871,929*** $8,548,571,808 ***$4,210,490,592***
Cancelled due to maintenance ***Saving*** Delayed due to maintenance ***Saving***	50%	$248,226,120 ***$248,226,120*** $4,670,728,200 ***$4,670,728,200***	$496,452,240 ***$496,452,240*** $4,328,967,600 ***$4,328,967,600***	$62,056,530 ***$62,056,530*** $4,101,127,200 ***$4,101,127,200***	$186,169,590 ***$186,169,590*** $6,379,531,200 ***$6,379,531,200***

Table 4: Estimated annual potential savings globally through a reduction in unscheduled maintenance by cause: 2025, 2035

The potential savings from real-time adverse weather avoidance include a reduction in delays, cancellations and unscheduled maintenance, including airframe inspections. These are required when aircraft have flown through conditions that can result in a compromised structure or damage that requires further investigation, including lightning strikes. Lightning strikes can affect airline operations and cause costly delays and service interruptions.[76] Around one-third of lightning damage occurs within the allowable damage limit,[77] but in other cases, severe damage may require extensive repairs that can remove an airplane from service for an extended period of time.[78] Limited information exists on the cost of lightning strikes, with data from 2002 indicating that in the US, the cost of lightning strikes to airlines' operating costs and passenger delays was US$2 billion.[79] Aircraft are struck on average between once or twice per annum, or every 1,500 to 3,000 hours,[80] with the average cost per inspection for a narrow body aircraft around US$19,000.[81]

The Federal Aviation Administration's (FAA) Aviation Research Program Team has developed the National Convective Weather Forecast (NCWF) product to improve knowledge of current weather conditions: *"The technology used to create these products includes a combination of radar and satellite data, surface weather observations, numerical weather models and pilot reports. These* *products enable users to better anticipate where icing hazards may be encountered, and allow air traffic controllers to make more informed decisions when rerouting aircraft and assigning holding altitudes."* [82] Target users are airline dispatchers, General Aviation, FAA Traffic Management Units (TMU), and agencies that provide accurate forecasts to connected aircraft.[83] The Met Office in the UK provides a comparable service.

No Fault Found

Enhanced data streaming capabilities can reduce 'No Fault Found' (NFF). Airlines indicate that a single LRU programme that removes and tests 25–30 units a year can incur costs of around US$30,000 with a 60% NFF.[84] Airline managers interviewed identified the rate for this type of fault at 25%–30% of all avionics removals, often due to visual inspection only identifying 25% of problems,[85] and highlighted that real-time, continuous monitoring to reduce NFF was a key consideration for a connected aircraft. Data indicate that the cost per aircraft for NFF on average was US$150,000,[86] equating to US$3.3 billion globally per annum. A reduction in NFF of 5%, 15%, 25% and 40% equates to a saving of US$168 million, US$506 million, US$844 million and US$1.3 billion respectively.[87] Airline managers indicated that they were targeting a reduction of a 5–15% reduction on NFF faults initially due to connected aircraft benefits, increasing over time.

Resale Value

Digitised maintenance records can display real-time current maintenance status that lessors can utilise to obtain accurate estimates of the value of their assets,[88] whilst identifying if preventative maintenance is required to reduce the chance of an unplanned event that results in AOG. Increasingly accessible flight and maintenance history can maximise aircraft resale value.[89] The current prevalence of paper reports increases the risk of incomplete records, in turn leading to parts often being 'pulled' and replaced. Additional costs are also incurred in the due diligence process of a sale to validate missing or incomplete records.[90] These can reach US$1 million per aircraft for a narrow body aircraft and US$2m for a wide body aircraft.[91] Based on current aircraft numbers and 40% leased rates, this equates to an additional cost of US$6.7 billion for narrow body and US$4.5 billion for wide body aircraft, totalling US$11.2 billion.[92] Connectivity can reduce this cost by generating electronic job cards and linking to on-board technology. Interviews indicate that operations managers in some airlines are already utilising on-board data and integrating with maintenance suppliers, to enable the extraction of relevant data from specific aircraft documents and match records to the maintenance tasks. If this integration lowered costs by 10%, 25% and 50%, it could deliver annual cost savings of US$1.1 billion, US$2.8 billion and US$5.6 billion respectively.[93] Many airline managers indicated that they are already incorporating digitalisation in their operational processes with connected aircraft, and are expecting savings of at least 25%–50% in the next five years.[94]

Aircraft Health Monitoring

A Boeing 787 can generate 500GB of data per flight,[95] while short-medium haul flights can generate 40–50GB of data.[96] Advanced wide body aircraft are expected to produce five to eight terabytes of data per flight:[97] each flight of a new generation aircraft is forecast to create around 30 times more data than the older generation it is replacing.[98] By 2026, the annual data generated by aircraft is estimated to be 98 billion gigabytes.[99]

To date, engine data has primarily been stored in a static manner on board the aircraft in a series of reports. This information is downloaded when a plane lands; with higher bandwidth, on-board sensors can continuously measure engine performance with this data streamed or polled at defined intervals to track pressure, low-end and high-end rotor speeds, temperatures, vibration and other parameters across the full-flight profile, permitting health monitoring in real-time. This permits airline operations teams to pinpoint faults before they become major problems,[100] and utilise the information to make informed decisions that can reduce unscheduled AOG. This capability can result in reduced cancellations; improved operational and flight safety; reduced fuel consumption; the identification of serial numbers and parts requiring attention; and enhance the flight experience for passengers and crew.
With the advent of connected engines within the IoT, OEMs and engine manufacturers can link individual engines in cloud platforms with other relevant data on airports, transport sites, maintenance centres and other aircraft.

Changes in the engine supply market have also altered the business model and dynamics of engine use. Interviews with airline managers indicate that they are increasingly utilising 'power by the hour' contracts with engine suppliers. A connected aircraft offers the potential for real-time engine monitoring through streaming or polling that can harness cloud and computing power located off the aircraft to provide more accurate monitoring of critical assets.[101] This can enable innovative commercial contracts that reflect factors such as engine use, route allocation and the impact of flying through polluted airspace.

Other areas of maintenance can benefit from a similar commercial arrangement. Interviews with airlines and third-party suppliers indicate that by monitoring brake use, including the measurement of 'hard' and 'soft' landings, pricing could be based on performance. The use of this aircraft data could lead to a more agile insurance offering, with underwriting based on airlines' ratings, including how aircraft land and the rate at which materials such as brakes and tyres are replaced. This could be further extended to pilot insurance: pilots could be rated based on how they have flown aircraft, with a data profile built up over time. These opportunities can ensue through the targeted utilisation of data generated by the connected aircraft.

Data Off-Loading

Connected aircraft can automate the data off-load process currently occurring at the end of a flight. To date, this occurs through the use of portable hard drives, memory cards or USB devices plugged into the engine data computer. Downloaded text files are subsequently transmitted via email by the airline or its service provider to the engine manufacturer. Limited use of ground-based terrestrial Wi-Fi or mobile networks such as 4G occurs due to bandwidth limitations that constrain the data that can be transmitted. Often, this is not possible due to a lack of mobile coverage and airport mobile 'black spots'. As the volume of data generated grows, such processes will prove problematic in the expedient downloading of information. With over 40GB of data stored on-board an average short-medium haul flight, data size limits the use of off-loading through a mobile mode.[102] A connected aircraft can minimise the requirement to off-load data at the end of its flight by streaming en route or polling from the ground. In addition, this 'pulls forward' post-flight diagnosis and can alert the OCC to any issues that require intervention, resulting in significant savings.

Predictive Maintenance

With the advent of predictive techniques, parts can be replaced that are identified as targets for replacement before they fail. This permits airlines to provision and locate replacements and engage labour more efficiently. Technology providers and industry specialists interviewed indicate that advancements in software will continue to result in more accurate predictive functionality that is likely to be able to alert airlines in advance when to repair a component. This can reduce costs, enhance safety, and innovate service delivery through specialised third-party management of critical components.

Both Airbus and Boeing are developing interfaces to permit complete aircraft sensor data retrieval that enables predictive maintenance through remote diagnostics and the ability to:

- Stream or transmit triggered critical Airbus FOMAX server data to the 'Skywise' Data Lake;
- Stream or transmit triggered critical Boeing ONS server data to 'ANALYTZ'.

Beginning in 2018, Airbus' new A320s will use a secure server router that collects aircraft maintenance and performance data and automatically transmits this to ground-based operations via 4G on the ground, and satcom broadband in the air, in contrast to the legacy low-bandwidth ACARS network.[103] This represents a significant improvement on existing capability: current A320s capture only 2% of the available data transmitted by their aircraft health status computers (400 health parameters), compared to FOMAX-enabled A320s that capture 100% of the available data (more than 24,000 health parameters).[104] Both Airbus and Boeing are extending data collection with new aviation data platforms that offer a single access outlet for data analytics. This combines many sources into a single, secure, cloud-based platform that could potentially be used to generate work orders, spares consumption, components data, aircraft and fleet configuration and flight schedules.[105] These platforms provide airlines with operational insights and can integrate with reporting, alerting, and other preventive maintenance elements.

A connected aircraft offers the potential to utilise predictive maintenance and minimise AOG time: costs vary between US$10,000-US$150,000 per hour, depending on the aircraft size, load, airport, and other factors, and US$100,000–US$1.2 million per day.[106] Globally, AOG is estimated to cost the airline industry US$62 billion annually.[107] This figure reflects the significant cost of an aircraft's lease payments; passenger re-scheduling; compensation; lost revenue; replacement flights; additional personnel costs; hangar and other apron fees; and other costs. Predictive maintenance can highlight potential issues and improve planning, resulting in greater certainty for arrivals and departures. It can also lower costs through a reduction in aircraft malfunctions in less accessible airports. AOG costs can also be reduced through adverse weather avoidance and other preventative measures afforded by transmitting real-time information to the aircraft. Industry interviews and analysis of current AOG costs and contributing factors reveal a broad range of expected benefits enabled by a connected aircraft. AOG reductions of 5%, 20%, 50% or 75% could result in savings of US$3 billion, US$15 billion, US$31 billion, and US$46 billion respectively.[108] Airline managers indicate that AOG remains one of the most significant areas for improvement, but with uncertainty, in this early stage of connected aircraft penetration, of the scale of the benefits that can be realised. A target 5%–15% cost reduction was identified for the near term.

Airline Operations Control Services

Inflight connectivity offers a range of benefits for *Airline Operations Control.* Eight categories have been identified: *Disruption Management; Crew Connectivity and Crew Efficiency; Situational Awareness; Irregular Operations; Flight Optimisation; Safety and Operational Risk Reduction; Environmental Factors; and Compliance with Future Regulations.* A number of benefits offered by areas within some categories are not currently obtainable until enabling elements develop further, including regulatory factors, standards, and others. The identified benefits are depicted in Figure 7:

Figure 7: Connected Airline Operations Control Services

Crew Connectivity

The connected aircraft has the potential to transform how flight and cabin crews work and communicate. The primary benefits include:

Flight Crew

- Traditional pilots' flight bags can be replaced by connected digital EFBs, saving weight while enhancing productivity and efficiency.[109]
- Pilot Flight Briefs can be digitally transmitted to aircraft directly in the air.
- Flight plans and data-heavy applications can be pre-installed in an EFB before a flight. The crew can utilise this to view airport and departure charts, calculate take-off performance and commence checklists.
- In-air EFB updates can provide efficiency-enhancing data, such as graphical weather, telemedicine, passenger information, aircraft documentation and others.[110]
- Amendments to the flight can be made in real-time and transmitted to the OCC by the pilot in addition to the review of maintenance logs, weather, and minimum equipment log descriptions.
- A continuous secure data exchange can occur between ground operations and the aircraft with real-time telemetry, tracking, and flight data streaming, including Black Box in the Cloud™ features.
- Data processing can shift off the plane to a centralised function at fleet level, increasing computing power dramatically and permitting calculations to occur using principal data. Data can subsequently be streamed to the FMS using the defined Cost Index, facilitating required adjustments to optimise the flight.

Cabin Crew

- Cabin crew briefs can be delivered directly to crew devices in the cabin, including passenger lists currently provided manually at the gate by the ground crew.
- Post-flight, the flight crew can file the pilot log, journey report, and the final flight folder. In addition, performance calculations can be sent where they are not being automatically provided or polled, and maintenance records updated.

- Voyage reports and cabin reports can be submitted without visiting the Crew Room.
- Serious Safety Forms can be submitted inflight for arrival resolution.

Virtual Crew Room

In the absence of reliable airport Wi-Fi, satcom connectivity can transform the aircraft into a virtual Crew Room. This eliminates the requirement for flight crew to visit a dedicated facility in the airport before the flight. This maximises on-time departure while concurrently potentially resulting in a later crew arrival time at the airport.[111] Between 20%–55% of crews commute from outside the area they are based.[112] This can impact on-time departure of first flights, and affect subsequent arrival and departure times for that aircraft for the rest of the day. Data indicate that airline delays caused by crew scheduling (including late arrival for a first or subsequent flight) accounted for around 3% of an airline's total flights, and were the cause of cancellations in around 0.025% of those flights.[113]

With around 37 million annual flights globally, the estimated cost of cancelled flights due to crew scheduling is estimated to be US$220 million annually. Reducing this by connecting crews and the OCC can deliver significant savings through direct-to-plane arrival, downloading plans to aircraft and devices, and removing the need for additional visits to lodge flight plans. In the case of crews en route, real-time data transmission from the aircraft can provide updates directly to the OCC to automatically alert when a crew delay could occur.

Interviews with airline managers indicate that speculative routes - these are routes that can be developed on short notice for a limited time to a destination, subject to the required approvals being granted - are an emerging area of consideration and could account for 1%–2% of total revenue. Utilising public domain fleet and financial data from EasyJet, one of the leading low-cost European carriers, this can potentially generate an additional US$134 million per annum in revenue and US$14 million in profit for a 2% revenue contribution.[114] This results in the requirement for an additional three and six aircraft for a 1% and 2% contribution respectively. Table 5 depicts the potential revenue and profit contribution for a single A320 aircraft annually and over its estimated operating life.

Period	A320	
	Revenue	***Profit***
Annual	$22,380,356	$2,375,246
Lifetime	$559,508,903	$59,381,161
Average per PAX	**$78.05**	**$8.28**

Table 5: Revenue and profit contribution of a single aircraft for new 'opportunistic' routes[115]

Flight Optimisation

Flight optimisation encompasses a range of measures, including route planning, separation minima and trajectory-based operations, covered in detail later in this report. This section reviews the benefits of real-time weather and environmental data available to the flight crew and AOC.

Live Weather

The FAA identified weather as responsible for nearly 70% of all flight delays.[116] Weather is also a contributing factor in around 23% of aviation accidents and contributes to accident damage, injuries, and unscheduled maintenance.[117] The connected aircraft offers pre- and post-departure opportunities to improve navigation and avoid adverse weather that could deliver annual cost savings of US$1.3 billion:[118]

- Live weather updates can be streamed to pilots through EFBs to improve situational awareness and support decision-making during severe or extreme weather events. Information can be delivered via tablets running iOS, Windows or Android, certified for cockpit use since 2011 in the US.[119] Industry interviews indicate that this capability can:
    - Reduce paper-based weather forecast reports;

  - o Replace en route periodic radio dispatch updates;
  - o Provide enhanced data on winds and potential areas of clear air turbulence (CAT);
  - o Provide visual weather information, cloud heights and winds derived from satellite data.

- Speed and other parameters influencing the Cost Index calculations for fuel performance can be optimised.

- These enhancements facilitate dynamic routing. Pilots can avoid areas of severe weather with greater confidence and precision, yielding fuel savings, improved safety and lower CO_2 emissions.[120] Industry discussions and trial results indicate estimated annual savings from this approach are around 1% of fuel burn.[121] This equates to potential annual savings of 3.39 billion litres, 8.3 million tons of CO_2 and a cost saving globally of US$1.3 billion, based on current annual global fuel consumption.[122]

- Aircraft can act as nodes, transmitting weather data to the OCC, with this transmitted on to other aircraft flying close by. In addition, interviews indicate that some airlines transmit satellite images to provide pilots with a real-time visual representation of weather conditions.

- Real-time weather updates provide pilots enhanced situational awareness and support improved decision-making to enhance flight efficiency and improve flight planning. This can be utilised to avoid hazardous conditions; reduce delays and diversions; lower anti-ice usage; and decrease maintenance costs and downtime.[123]

Turbulence

Severe turbulence can increase fuel burn.[124] This occurs when flight crews seek alternative altitudes, or take unnecessary or excessive diversions around areas of assumed or last reported turbulence. The connected aircraft can reduce these activities, resulting in fuel savings, significant cost efficiencies and lower emissions. The Traffic Aware Strategic Aircrew Request (TASAR) concept has simulated on-board automation advising the pilot of beneficial, traffic-compatible trajectory changes, estimating a saving of between 900 to 1,300 minutes annually per aircraft and 8,000 to 12,000 gallons of fuel.[125] Alaska Airlines participated in trials and achieved estimated annual savings in fuel, maintenance and depreciation of more than US$5 million.[126] Industry discussions indicate an expected estimated range of savings of 1%–2% of annual global fuel burn, equating to 3.39 billion–6.7 billion litres annually, 8.5 million–17 million lower tonnes of CO_2 and lower costs of US$1.3 billion-US$2.6 billion. Other research indicates that IP-connectivity for weather tracking could result in annual fuel burn savings of US$30,000 per aircraft.[127]

Severe turbulence also increases maintenance costs due to aircraft inspection and repair, as well as associated costs from AOG.[128] The current global unscheduled cost due to turbulence is estimated to be US$456 million, comprised of maintenance, safety and other areas.[129] Data are difficult to obtain for the airframe inspection component: interviews with airline operations managers indicate a range of 5%–25% of this unscheduled cost.[130] A mid-range saving of 10% yields a global cost of US$45.6 million, affecting around 2,412 planes per annum for inspection, with an average cost per inspection of US$18,000 for a wide body aircraft.[131] These inspections require a large proportion of a day to complete, as they require scrutiny of the fuselage and damaged areas. Solutions such as the Turbulence Auto-PIREP System (TAPS) can reduce damage and airframe inspections.[132] Reports are processed and distributed by a server network to participating airlines immediately after they are generated. The advent of high-speed broadband will enhance this. Based on tests with TAPS reporting code installations in over 500 aircraft that have been broadcasting in-service turbulence reports globally,[133] it is estimated that a 98% reduction in unnecessary airframe inspections due to turbulence encounters could be possible.[134] This would yield an annual saving of US$44.7 million, excluding AOG costs. Table 6 depicts this reduction and a 10% and 50% reduction for 2017. The regional segmentation reflects the current distribution of passenger traffic from IATA.

		Airframe Inspection		Reduction in unnecessary Airframe Inspection		
Region	**All Turbulence Cost**	**Proportion**	**Costs**	**10%**	**50%**	**98%**
Asia Pacific	$166,666,667	10%	$16,666,667	$1,666,667	$8,333,333	$16,333,333
Africa	$13,789,954	10%	$1,378,995	$137,900	$689,498	$1,351,416
Middle East	$21,232,877	10%	$2,123,288	$212,329	$1,061,644	$2,080,822
Europe	$115,525,114	10%	$11,552,511	$1,155,251	$5,776,256	$11,321,461
North America	$100,000,000	10%	$10,000,000	$1,000,000	$5,000,000	$9,800,000
Latin America	$39,086,758	10%	$3,908,676	$390,868	$1,954,338	$3,830,502
Total	**$456,621,005**		**$45,630,137**	**$4,563,014**	**$22,815,068**	**$44,717,534**
Average cost/inspection			$18,919			
Aircraft affected			2,412			
% affected from global aircraft in operation			11%			

Table 6: Turbulence and airframe inspection costs, and potential savings from avoidance: 2017

Between 2017–2035, the airframe inspection costs due to air turbulence are forecast to grow as aircraft numbers double by 2035. Table 7 depicts a forecast growth of these costs to 2035.

Region	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Asia Pacific	$166,666,667	$173,250,000	$180,093,375	$187,207,063	$194,601,742	$202,288,511	$210,278,907	$218,584,924	$227,219,029	$236,194,180
Africa	$13,789,954	$14,334,658	$14,900,877	$15,489,461	$16,101,295	$16,737,296	$17,398,419	$18,085,657	$18,800,040	$19,542,642
Middle East	$21,232,877	$22,071,575	$22,943,403	$23,849,667	$24,791,729	$25,771,002	$26,788,957	$27,847,120	$28,947,082	$30,090,491
Europe	$115,525,114	$120,088,356	$124,831,846	$129,762,704	$134,888,331	$140,216,420	$145,754,969	$151,512,290	$157,497,025	$163,718,158
North America	$100,000,000	$103,950,000	$108,056,025	$112,342,238	$116,761,045	$121,373,107	$126,167,344	$131,150,954	$136,331,417	$141,716,508
Latin America	$39,086,758	$40,630,685	$42,235,597	$43,903,903	$45,638,107	$47,440,812	$49,314,725	$51,262,656	$53,287,531	$55,392,389
Total	**$456,621,005**	**$474,657,534**	**$493,406,507**	**512,896,064**	**$533,155,458**	**$554,215,099**	**$576,106,595**	**$598,862,806**	**$622,517,887**	**$647,107,343**

Region	2027	2028	2029	2030	2031	2032	2033	2034	2035
Asia Pacific	$245,523,850	$225,222,043	$265,303,313	$275,782,794	$286,676,214	$297,999,925	$309,770,922	$322,066,873	$333,333,333
Africa	$20,314,576	$21,117,002	$21,951,123	$22,818,193	$23,719,511	$24,656,432	$25,630,361	$26,642,760	$27,579,909
Middle East	$31,279,066	$32,514,589	$33,798,915	$35,133,972	$36,521,764	$37,964,374	$39,463,967	$41,022,793	$42,465,753
Europe	$170,185,025	$176,907,334	$183,895,173	$191,159,033	$198,709,814	$206,558,852	$214,717,927	$223,199,285	$231,050,228
North America	$147,314,310	$153,133,226	$159,181,988	$165,469,676	$172,005,729	$178,799,955	$185,862,553	$193,204,124	$200,000,000
Latin America	$57,580,388	$59,854,813	$62,219,078	$64,676,732	$67,231,463	$69,887,106	$72,647,646	$75,517,228	$78,173,516
Total	**$672,668,083**	**$699,238,473**	**$726,858,392**	**$755,569,299**	**$785,414,286**	**$816,438,150**	**$848,687,457**	**$882,210,612**	**$913,242,009**

Table 7: Turbulence and airframe inspection costs: 2017–2035

The potential savings that can accrue from the reduction of airframe inspection are depicted in Table 8. Industry discussions and interviews with airline managers indicate that as the penetration of connected aircraft continues, weather avoidance capability could reduce aircraft inspections caused by severe turbulence.

Saving rate	10%	10%	10%	15%	15%	20%	20%	25%	30%	35%
Region	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**
Asia Pacific	$16,666,667	$17,325,000	$18,009,338	$28,081,059	$29,190,261	$40,457,702	$42,055,781	$54,646,231	$68,165,709	$82,667,963
Africa	$1,378,995	$1,433,466	$1,490,088	$2,323,419	$2,415,194	$3,347,459	$3,479,684	$4,521,424	$5,640,012	$6,839,925
Middle East	$2,123,288	$2,207,158	$2,294,340	$3,577,450	$3,718,759	$5,154,200	$5,357,791	$6,961,780	$8,684,125	$10,531,572
Europe	$11,552,511	$12,008,836	$12,483,185	$19,464,406	$20,233,250	$28,043,464	$29,150,994	$37,878,072	$47,249,108	$57,301,355
North America	$10,000,000	$10,395,000	$10,805,603	$16,848,636	$17,514,157	$24,274,621	$25,233,469	$32,787,739	$40,899,425	$49,600,778
Latin America	$3,908,675	$4,063,068	$4,223,560	$6,585,585	$6,845,716	$9,488,162	$9,862,945	$12,815,664	$15,985,259	$19,387,336
Total	**$45,662,100**	**$47,465,753**	**$49,340,651**	**$76,934,410**	**$79,973,319**	**$110,843,020**	**$115,221,319**	**$149,715,701**	**$186,755,366**	**$226,487,570**

Saving rate	40%	50%	60%	65%	75%	80%	85%	90%	90%	
Region	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**Total**
Asia Pacific	$98,209,540	$127,611,021	$159,181,988	$179,258,816	$215,007,161	$238,399,940	$263,305,284	$289,806,186	$300,000,00	$2,268,045,647
Africa	$8,125,830	$10,558,501	$13,170,674	$14,831,825	$17,789,634	$19,725,146	$21,785,807	$23,978,484	$24,821,918	$187,657,475
Middle East	$12,511,626	$16,257,294	$20,279,349	$22,837,082	$27,391,323	$30,371,499	$33,544,372	$36,920514	$38,219,178	$288,942,802
Europe	$68,074,010	$88,453,667	$110,337,104	$124,253,371	$149,032,361	$165,247,082	$182,510,238	$200,879,356	$207,945,205	$1,572,097,394
North America	$58,925,724	$76,566,613	$95,509,193	$107,555,290	$126,004,296	$143,039,964	$157,983,170	$173,883,712	$180,000,000	$1,360,827,388
Latin America	$23,032,155	$29,927,407	$37,331,447	$42,039,876	$50,423,597	$55,909,685	$61,750,499	$67,965,506	$70,356,164	$531,903,308
Total	**$269,067,233**	**$349,619,236**	**$436,115,035**	**$491,120,044**	**$589,060,715**	**$653,150,520**	**$721,384,339**	**$793,989,551**	**$821,917,808**	**$6,213,823,691**

Table 8: Potential airframe savings: 2017–2035

The growing penetration of connected aircraft is forecast to result in reduced inspections by 2035, yielding a cumulative potential saving between 2017–2035 of over US$6 billion.

An additional major cost incurred by airlines as a result of severe turbulence is AOG. The total global AOG cost has been estimated to be US$62 billion in 2016.[135] Industry discussions indicate an estimate for the proportion of AOG that is attributed to severe weather damage or repairs between 2%–5%, yielding a global cost of US$1.2 billion–US$3 billion annually. A range of 33%–66% is attributed to airframe inspections and follow-on repairs, yielding a cost of US$409 million-US$806 million annually for the US$1.2 billion cost and US$1 billion–US$2 billion for the US$3 billion cost respectively.

Some US airlines have adopted broadband connectivity to access real-time weather updates including enhanced turbulence information along with conductive and convective weather.[136] In addition, some European international airlines have also been using IP-enabled applications to enhance efficiency and weather planning: *"This set-up allows us to implement new requirements and processes such as inflight flight planning and up-to-date transfer of weather data more flexibly and with less resources in order to optimise our flight management and in the end, of course, our customer service."*[137] Research indicates that weather management can also deliver benefits through:

1. Increasing airport capacity by 10% during adverse weather may yield a 20%–50% reduction in total system delays.[138] The use of weather data and reduced separation can improve airport utilisation:
    - Current global delay costs are estimated to be US$121 billion across airlines and passengers.[139] Delays due to weather account for around 33% of total delays: US$39.9 billion annually. Using a reduction at the lower end of the estimated capacity, an increase of 10% could yield a corresponding saving of US$3.9 billion per year to airlines and passengers, comprised of US$1.3 billion and US$2.6 billion respectively. A 50% reduction in delays could yield a cost reduction as great as US$19 billion and savings of US$6.6 billion and US$13.3 billion respectively annually.

2. Small reductions in the effective duration of adverse weather can reduce total system delays by 20%–35%:[140]
    - Based on the same delay costs and weather contribution as the airport capacity example, a system delay reduction of 20% could yield a corresponding saving of US$7.9 billion annually for airlines and passengers, comprised of US$2.6 billion and US$5.3 billion respectively. A 35% system delay reduction could yield a cost reduction of US$13.9 billion and a saving of US$4.6 billion and US$9.3 billion respectively annually.

Turbulence and Injuries

The cost to US airlines of weather-related flight attendant and passenger accidents has been estimated to be between US$100m[141] –US$200m[142] annually. Turbulence is the leading cause of non-fatal, weather-related injuries in the commercial airline industry,[143] with research on turbulence avoidance by NASA highlighting; *"If the pilot receives a timely and reliable turbulence alert, passengers and flight attendants can be warned and securely seated; thereby, removing them from the risk of injury."*[144] Although some data are available from agencies such as the FAA, extensive discussions with airlines and other industry specialists on inflight injuries and their costs, frequency and related elements, indicate that the cost is likely to be higher than reported. This is also highlighted in other research: *"The overall number of casualties recorded globally each year is in the low hundreds; however, experts believe this is due to under-reporting of minor injuries and the true number is significantly higher."*[145] Some data indicate that for every report of a serious, turbulence-related injury to a flight attendant, around 70 'minor' injuries occur.[146] Despite these often unreported injuries not being classed as 'serious', they account for lost days, treatment and trauma and contribute to costs[147] and staffing challenges for airlines.[148] Additional studies support the notion that turbulence-related injuries may be grossly understated.[149]

The incidence of weather-related injuries peaked in the latter part of the 1990s at 1,862, double the rate that was reported from 1980–1995.[150] The current number of passengers injured globally varies by over 150% year-by-year, between 2013 and 2016 inclusive, with detail for some regions difficult to obtain.[151] An estimated 200 passengers could be injured by turbulence globally each year,[152] with both crew and passengers affected by weather-related injuries. Flight attendants represent around 4% of aircraft occupants, but account for 52% of serious and fatal injuries, while passengers account for around 94% and 48% of these injuries respectively.[153]

Meteorological research and simulations forecast that by 2050, the number of inflight injuries could triple in line with an increased volume of CO_2, which may lead to increased CAT.[154] Flights to popular destinations are projected to experience the largest increases, with severe turbulence occurring two or three times more frequently throughout the year, including increases over the North Atlantic of 180%, Europe 160%, North America 110%, the North Pacific 90%, and Asia 60%.[155] In addition, the airspace in which severe turbulence occurs is forecast to increase over South America by 60%, Australia 50%, and Africa 50%.[156] These factors, driven by growth in air traffic, place increased urgency on injury reduction. Industry experts in CAT and severe weather highlight that *"unless aviation meteorologists become better at forecasting patches of turbulence, passengers will face increased discomfort levels from inflight bumpiness and an increased risk of injury."*[157]

Using data from airline interviews, government air transport agencies, the insurance industry and other consolidators of injury costs from weather-related injuries during flight, it is estimated that in 2017, a global cost of US$367 million was attributable to this type of injury, and could reach US$1 billion by 2035. Cumulatively by 2035, this equates to US$12.1 billion, as depicted in Table 9. If mitigating measures are used to reduce the proportion of injuries, cost savings will occur. A range of reductions has been estimated including 10%, 25%, 50% and 75%, yielding potential savings against the forecast costs for 2035 of US$61 million, US$152 million, US$305 million and US$458 million respectively.

Reduction via Connectivity	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Current	**$367,506,458**	**$388,866,488**	**$411,467,995**	**$435,383,137**	**$460,688,262**	**$487,464,159**	**$515,796,312**	**$545,775,173**	**$577,496,450**	**$611,061,416**
Flight Attendants	$191,103,358	$202,210,574	$213,963,358	$226,399,231	$239,557,896	$253,481,363	$268,214,082	$283,803,090	$300,298,154	$317,751,936
PAX	$176,403,100	$186,655,914	$197,504,638	$208,983,906	$221,130,366	$233,982,797	$247,582,230	$261,972,083	$277,198,296	$293,309,480
10.00%	**$330,755,812**	**$349,979,839**	**$370,321,196**	**$391,844,823**	**$414,619,436**	**$438,717,743**	**$464,216,681**	**$491,197,656**	**$519,746,805**	**$549,955,274**
Flight Attendants	$171,933,022	$181,989,516	$192,567,022	$203,759,308	$215.602.107	$228,133,277	$241,392,674	$255,422,781	$270,268,339	$282,976,743
PAX	$158,762,790	$167,990,323	$177,754,174	$188,085,515	$199,017,329	$210,584,517	$222,824,007	$235,774,875	$249,478,466	$263,978,532
Saving	**$36,750,646**	**$38,886,649**	**$41,146,800**	**$43,538,314**	**$46,068,826**	**$48,746,416**	**$51,579,631**	**$54,577,517**	**$57,749,645**	**$61,106,142**
25.00%	**$275,629,843**	**$291,649,866**	**$308,600,997**	**$326,537,352**	**$345,516,196**	**$365,598,120**	**$386,847,234**	**$409,331,380**	**$433,122,338**	**$458,296,062**
Flight Attendants	$143,327,519	$151,657,930	$160,472,518	$169,799,423	$179,668,422	$190,111,022	$201,160,562	$212,852,317	$225,223,616	$238,313,952
PAX	$132,302,325	$139,991,936	$148,128,478	$156,737,929	$165,847,774	$175,487,097	$185,686,672	$196,479,062	$207,898,722	$219,982,110
Saving	**$91,876,614**	**$97,216,622**	**$102,866,999**	**$108,845,784**	**$115,172,065**	**$121,866,040**	**$128,949,078**	**$136,443,793**	**$144,374,133**	**$152,765,354**
50.00%	**$183,753,229**	**$194,433,244**	**$205,733,998**	**$217,691,568**	**$230,344,131**	**$243,732,080**	**$257,898,156**	**$272,887,586**	**$288,748,225**	**$305,530,708**
Flight Attendants	$95,551,679	$101,105,287	$106,981,679	$113,199,616	$199,778,948	$126,740,681	$134,107,041	$141,901,545	$150,149,077	$158,875,968
PAX	$88,201,550	$93,327,957	$98,752,319	$104,491,953	$110,565,183	$116,991,398	$123,791,115	$130,986,042	$138,599,148	$146,654,740
Saving	**$183,753,229**	**$194,433,244**	**$205,733,998**	**$217,691,568**	**$230,344,131**	**$243,732,080**	**$257,898,156**	**$272,887,586**	**$288,748,225**	**$305,530,708**
75.00%	**$91,876,614**	**$97,216,622**	**$102,866,999**	**$108,845,784**	**$115,172,065**	**$121,866,040**	**$128,949,078**	**$136,443,793**	**$144,374,113**	**$152,765,354**
Flight Attendants	$47,775,840	$50,552,643	$53,490,839	$56,599,808	$59,889,474	$63,370,341	$67,053,521	$70,950,772	$75,074,539	$79,437,984
PAX	$44,100,775	$46,663,979	$49,376,159	$52,245,976	$55,282,591	$58,495,699	$61,895,557	$65,493,021	$69,299,574	$73,327,370
Saving	**$275,629,843**	**$291,649,866**	**$308,600,997**	**$326,537,352**	**$345,516,196**	**$365,598,120**	**$386,847,234**	**$409,331,380**	**$433,122,338**	**$458,296,062**

Reduction via Connectivity	2027	2028	2029	2030	2031	2032	2033	2034	2035	Total
Current	**$646,577,228**	**$684,157,273**	**$723,921,527**	**$765,996,939**	**$810,517,838**	**$857,626,358**	**$907,472,897**	**$960,216,592**	**$1,016,025,830**	$12,174,018,332
Flight Attendants	$336,220,159	$355,761,782	$376,439,194	$398,318,408	$421,469,276	$445,965,706	$471,885,907	$499,312,628	$528,333,432	$6,330,489,533
PAX	$310,357,069	$328,395,491	$347,482,333	$367,678,531	$389,048,562	$411,660,652	$435,586,991	$460,903,964	$487,692,399	$5,843,528,800
10.00%	**$581,919,505**	**$615,741,546**	**$651,529,374**	**$689,397,245**	**$729,466,054**	**$771,863,722**	**$816,725,607**	**$864,194,933**	**$914,423,274**	**$10,956,616,499**
Flight Attendants	$302,598,143	$320,185,604	$338,795,274	$358,486,567	$379,322,348	$401,369,136	$424,697,316	$449,381,365	$475,500,089	$5,697,440,580
PAX	$279,321,362	$295,555,942	$312,734,099	$330,910,678	$350,143,706	$370,494,587	$392,028,292	$414,813,568	$438,923,159	$5,259,175,920
Saving	**$64,657,723**	**$68,415,727**	**$72,392,153**	**$76,599,694**	**$81,051,784**	**$85,762,636**	**$90,747,290**	**$96,021,659**	**$101,602,583**	**$1,217,401,833**
25.00%	**$484,932,921**	**$513,117,955**	**$542,941,145**	**$574,497,704**	**$607,888,378**	**$643,219,769**	**$680,604,673**	**$720,162,444**	**$762,019,373**	**$9,130,513,750**
Flight Attendants	$252,165,119	$266,821,336	$282,329,395	$298,738,806	$316,101,957	$334,474,280	$353,914,430	$374,484,471	$396,250,074	$4,747,867,150
PAX	$232,767,802	$246,296,618	$260,611,750	$275,758,898	$291,786,422	$308,745,489	$326,690,243	$345,677,973	$365,769,299	$4,382,646,600
Saving	**$161,644,307**	**$171,039,318**	**$180,980,382**	**$191,499,235**	**$202,629,459**	**$214,406,590**	**$226,868,224**	**$240,054,148**	**$254,006,458**	**$3,043,504,583**
50.00%	**$323,288,614**	**$342,078,636**	**$361,960,763**	**$382,998,469**	**$405,258,919**	**$428,813,179**	**$453,736,449**	**$480,108,296**	**$508,012,915**	**$6,087,009,167**
Flight Attendants	$168,110,079	$177,880,891	$188,219,597	$199,159,204	$210,734,638	$222,982,853	$235,942,953	$249,656,314	$264,166,716	$3,165,244,766
PAX	$155,178,535	$164,197,745	$173,741,166	$183,839,265	$194,524,281	$205,830,326	$217,793,495	$230,451,982	$243,846,199	$2,921,764,400
Saving	**$323,288,614**	**$342,078,636**	**$361,960,763**	**$382,998,469**	**$405,258,919**	**$428,813,179**	**$453,736,449**	**$480,108,296**	**$508,012,915**	**$6,087,009,166**
75.00%	**$161,644,307**	**$171,039,318**	**$180,980,382**	**$191,499,235**	**$202,629,459**	**$214,406,590**	**$226,868,224**	**$240,054,148**	**$254,006,458**	**$3,043,505,584**
Flight Attendants	$84,055,040	$88,940,445	$94,109,798	$99,579,602	$105,367,319	$111,491,427	$117,971,477	$124,828,157	$132,083,358	$1,582,622,383
PAX	$77,589,267	$82,098,873	$86,870,583	$91,919,633	$97,262,141	$102,915,163	$108,896,748	$115,225,991	$121,923,100	$1,460,882,200
Saving	**$484,932,921**	**$513,117,955**	**$542,941,145**	**$574,497,704**	**$607,888,378**	**$643,219,769**	**$680,604,673**	**$720,162,444**	**$762,019,373**	**$9,130,513,749**

Table 9: Weather-related inflight costs and savings from enhanced detection, 2018–2035

Interviews with airline managers and others engaged in treating on-board weather-related injuries indicate that a reduction of at least 50% in the number of injuries could occur through enhanced navigational information. Segmenting current costs by IATA regions,[158] Europe accounts for the highest costs at US$115 million, followed closely by both Asia Pacific (US$111 million) and North America (US$100 million). Chart 1 depicts these costs in addition to those accruing to other major regions:

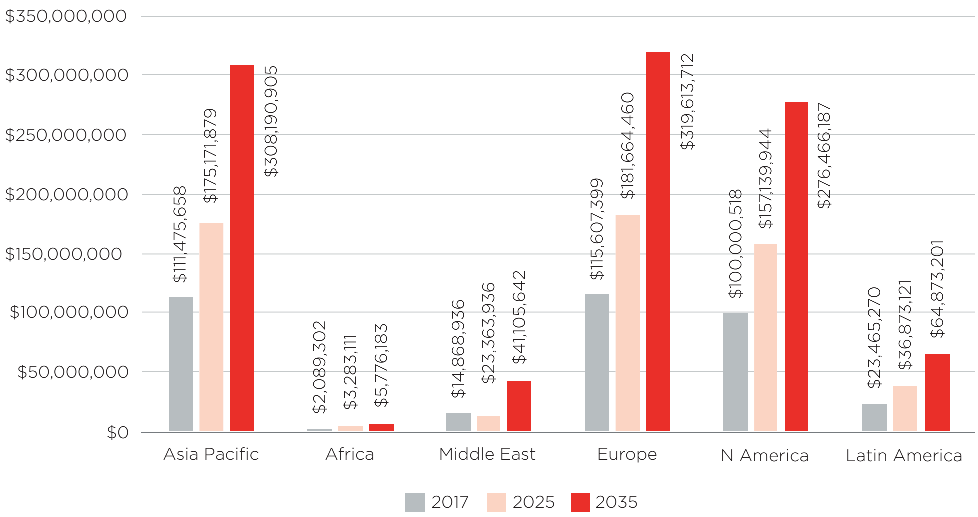

Chart 1: Regional distribution of weather-related injury costs – 2017, 2025, 2035

Key considerations for the results Include:

- The average cost of an injury in 2017 has been estimated to be US$66,000 in the US,[159] averaged across flight attendants and passengers;
- For other major regions, this figure has been adjusted to account for country-specific factors such as costs of living, medical costs, and other factors, with injury costs driven by regional passenger numbers as defined by IATA;[160]
- Injuries to flight attendants and other crew members occur as they undertake their duties in the cabin, while passengers are most often injured by not wearing a seatbelt or when items fall on them.[161]

FAA research has highlighted that the provision of high definition (visual) real-time information that enhances the pilot's ability to predict and avoid turbulence can result in fewer related accidents.[162] Improved cockpit connectivity can deliver real-time graphic weather and issue frequent operational forecasts that predict when and where adverse weather and turbulence will occur.[163] Digitalising this process can significantly enhance the existing manual process, as highlighted by NASA research: *"Currently, turbulence encounter reporting depends primarily on pilot reports (PIREPs) passed from the cockpit to controllers, briefers, and dispatchers via voice communications. These 'ride reports,' however, do not produce consistent, accurate, and timely reports of the location and severity of aircraft-encountered turbulence."*[164]

Environmental Factors

A connected aircraft can utilise real-time weather and other information to avoid flights through 'contaminated' airspace that can cause engine and fuselage damage and risk of accidents. Through integration into the IoT, each connected aircraft can act as a 'sensor' reporting conditions to other nearby aircraft, with maximum benefit accruing to aircraft that have not approached adverse areas.[165] This capability offers a significant benefit in the case of extreme events, such as volcano eruptions, that can occur with little or no warning and affect a large airspace. With such events, during the day, a pilot may interpret a dispersing ash cloud as water vapour and fly the aircraft into this area.[166] At night, ash clouds are not visible, increasing their hazard level significantly.[167]

Volcanic Ash Impact[168]

Around five volcanic eruptions occur each year in the North Pacific from Alaska to the Kuril Islands.[169] Ash clouds are subsequently carried to the east and northeast in the path of busy air corridors.[170] On average, volcanic ash is present five days a year above an altitude of 30,000 feet.[171] Ash clouds can also migrate significant distances from their origin, and can lead to high maintenance costs due to aircraft inspection and repair needs, as well as associated AOG losses.

Between 1953 and 2009, 129 reported ash cloud incidents have occurred.[172] Of these, 94 incidents have been confirmed as ash encounters, with 79 displaying various degrees of airframe or engine damage. Of the remainder, 20 have been low-severity events that are likely to have involved ash or gas clouds, whilst 15 have insufficient data to assess severity.[173] Of the damaging encounters, 26 involved significant to very severe damage to engines and/or airframes, including nine encounters that caused engine shutdown during flight.[174] The majority of damaging events have occurred within 24 hours of ash production and less than 1,000 kilometres from the source volcanoes.[175]

A single ash event can have significant costs for an airline. The replacement of an engine can cost between US$12million–US$35million;[176] maintenance, airframe inspection and repairs can cost between US$20,000–US$2 million or more, depending on the severity of the damage;[177] and AOG costs can be between US$20,000–US$1 million or more per day depending on aircraft size, passenger numbers, location and other logistical arrangements required.[178] Severe damage to a four-engine wide body can result in costs of US$80 million, and even cases with less severe damage can generate a total cost of US$5 million–US$15 million per aircraft.[179]

IP-enabled, real-time weather updates can assist in reducing the impact of extreme weather events.[180] Updates on volcanic activity can be delivered electronically to EFB apps, depicting areas of reported volcanic ash plumes, which in turn enable pilots to identify and avoid areas of ash concentration that could be hidden in areas of low visibility or heavy precipitation. This approach can also be utilised for atmospheric ice forecasting and avoidance.[181]

Irregular Operations

Aircraft diversions for medical emergencies have an economic, operational and social impact. This section reviews this irregular operation and the benefits that a connected aircraft could deliver.

Diversions for Medical Emergencies

Data on emergencies and diversions is fragmented and varies considerably between sources. Interviews highlight that diversion costs vary between regions, carriers, international and domestic flights, and other factors such as the location of alternative airports and accommodation cost. An international diversion can cost an airline US$200,000 for a wide body aircraft,[182] with the average estimated to be 50%–66% of this cost.[183] Diversions for a narrow body aircraft can range from US$15,000–US$25,000.[184/185] Although inflight medical emergencies occur frequently, minimal data exist on the detail of reported events. This research has reviewed available data from medical, airline and regulatory sources and complemented this with interviews with airline operations managers, safety specialists and other industry experts.

The research indicates that medical emergencies can be under-reported. These events have a significant cost, operational and social impact on airlines, crew, passengers and airports.[186] Passengers account for the majority of emergencies (94%), with crew comprising a relatively small proportion (6%).[187] The increase of urgent medical conditions during flights[188] is exacerbating demand for enhanced on-board treatment, with some airlines recording historically disproportionate increases in the frequency of inflight medical incidents and emergencies with respect to passenger numbers and the number of passenger-miles flown.[189] This is forecast to continue: by 2030, as the population ages further and the number of passengers flying doubles to approach 7 billion,[190] more than half of all passengers will be aged 50 and over. Around 5% of passengers currently suffer with chronic diseases, a proportion which is expected to increase.[191] This equates to around 200,000 passengers globally today, rising to around 360,000 by 2035.[192]

It is estimated that some form of on-board medical emergency occurs once in every 604 flights,[193] resulting in a total of around 61,000 emergencies globally in 2017, with 50 a day alone in the US.[194] Estimates of emergencies that result in a diversion vary significantly from 1%–13%,[195/196] with more recent research indicating that 7%–13% is a more reflective range.[197] This would equate to 610 diversions at 1%; 4,270 at 7%; and 7,921 at 13%. On-board mortality is estimated to be between 0.1%[198]–0.8%[199] per million passengers based on passenger and airline inflight emergency data.[200/201]

Limited research exists on the potential of emergencies to result in diversions and the factors that often precede this, but some evidence indicates:

- The categories of emergency not related to death but accounting for the most diversions are: neurological (39%); cardiac (23%); and obstetric and gynaecological (13%).[202]
- Key risk factors for diversion are increasing age, altered mental status and defibrillator (AED) use. Those requiring an AED are 35 times more likely to be diverted.[203]
- Unconscious passengers are 33 times more likely to require diversion.[204]
- Around 66% of inflight medical events could be related to pre-existing conditions,[205/206] along with age.[207]

These insights highlight how connectivity can enhance the on-board management of emergencies that can result in both diversions and passenger mortality. The current procedure for managing inflight medical emergencies relies on the use of on-board emergency medical kits by flight attendants, or medically trained passengers if they volunteer, in conjunction with organisations contracted by airlines to provide remote medical guidance. These remote resources include MedAire's *MedLink* service, which takes around 36,047 calls from airlines annually,[208] *The First Call* and *StatMD.* These services utilise a call centre to connect doctors with the aircraft. Integration between on-board and remote assistance is still relatively limited in terms of the two-way exchange of information and vital statistics.

Without greater data exchange and information between aircraft and medical specialists, airlines continue to incur significant costs from diversions that often ensue, creating additional operational issues and financial costs. These occur through pilot-initiated diversions that lack engagement between the flight crew and a medical professional, and which in some airlines can be as high as half of all diversions.[209] Airlines are increasingly seeking to leverage connectivity to enhance their telemedicine capability and reduce preventable diversions. Some studies have shown that, even with more rudimentary telemedicine, the number of diversions increased when the use of telemedicine decreased.[210] By contrast, connectivity can help reduce the incidence of diversions with research indicating:

- Emergency incidents are distributed proportionally to flight volumes: the frequency of incidents appears to be the same regardless of destination.[211]
- Around one-fifth of urgent medical requests on board are due to diagnostic problems, with enhanced tele-assistance an ideal approach to meeting this challenge.[212]
- Tele-assistance can be optimised and result in more accurate diagnoses with access to tangible data, such as pulse oximetry values and pulse and blood pressure values.[213] These are measured by a pulse oximeter, which some airlines are already using in combination with satcom connectivity.[214]
- Satellite connectivity can provide consistent coverage over traffic routes, permitting a continuous connection for critical discussions and data transfer with ground-based doctors.[215]
- Providers of satellite solutions, software and hardware are delivering IP-connected capability that prioritises emergency traffic over other traffic, ensuring unimpeded transport.[216]
- Greater bandwidth can enable the transmission of patient files, images and other information to assist an on-board medical professional in making an accurate diagnosis, potentially averting a diversion by using accurate, real-time data to manage a treatable condition.[217]
- The ability to transmit information between a connected aircraft and specialist medical ground teams can remove the constraints of a call centre environment and connect medical professionals regardless of location, ensuring critical patient information is transmitted immediately to where it is needed.[218]
- Reducing diversions can result in significant operational benefits for airlines and passengers, who can be stranded for periods that can include overnight stays or longer, sometimes in countries where immigration issues are created due to visa requirements or other documentation.
- Where a diversion is required, a connected aircraft can deliver key information to rapid response teams on the ground and the diversion hospital.

Using data from medical sources, airlines and other technology providers, the forecast cost of the 13% of medical emergencies that result in diversions for 2018 is US$552 million globally. This is estimated to increase in line with passenger growth to US$1.1 billion by 2035. Cumulatively over this period, the forecast cost is US$14.3 billion, as depicted in Table 10. By contrast, a reduction in diversion rates to 5%, enabled by effective telemedicine, would reduce the 2018 cost to US$212 million, increasing to US$428 million by 2035, with a cumulative total of US$5.5 billion over the period.

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027
Base Scenario	$552,007,950	$573,483,701	$596,076,914	$619,852,260	$644,878,389	$671,228,188	$698,979,050	$727,416,061	$757,345,100	$788,852,114

	Saving									
Diversion Reduction	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**
10%	$55,200,795	$57,348,370	$59,607,691	$61,985,226	$64,487,839	$67,122,819	$69,897,905	$72,741,606	$75,734,510	$78,885,211
25%	$138,001,988	$143,370,925	$149,019,228	$154,963,065	$161,219,597	$167,807,047	$174,744,763	$181,854,015	$189,336,275	$197,213,029
33%	$182,162,624	$189,249,621	$196,705,381	$204,551,246	$212,809,868	$221,505,302	$230,663,087	$240,047,300	$249,923,883	$260,321,198
50%	$276,003,975	$286,741,850	$298,038,457	$309,926,130	$322,439,195	$335,614,094	$349,489,525	$363,708,030	$378,672,550	$394,426,057
75%	$414,005,963	$430,112,776	$447,057,685	$464,889,195	$483,658,792	$503,421,141	$524,234,288	$545,562,046	$568,008,825	$591,639,086

	2028	2029	2030	2031	2032	2033	2034	2035	Total
Base Scenario	$822,028,275	$856,970,310	$893,780,849	$932,568,805	$973,449,765	$1,016,546,419	$1,061,935,791	$1,114,012,559	$14,301,412,500

	Saving								
Diversion Reduction	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**Total**
10%	$82,202,828	$85,697,031	$89,378,085	$93,256,880	$97,344,977	$101,654,642	$106,193,579	$111,401,256	$1,430,141,250
25%	$205,507,069	$214,242,577	$223,445,212	$233,142,201	$243,362,441	$254,136,605	$265,483,948	$278,503,140	$3,575,353,125
33%	$271,269,331	$282,800,202	$294,947,680	$307,747,706	$321,238,422	$335,460,318	$350,438,811	$367,624,144	$4,719,466,125
50%	$411,014,138	$428,485,155	$446,890,425	$466,284,402	$486,724,883	$508,273,210	$530,967,896	$557,006,280	$7,150,706,250
75%	$616,521,206	$642,727,732	$670,335,637	$699,426,604	$730,087,324	$762,409,814	$796,451,843	$835,509,419	$10,726,059,375

Table 10: Base scenario diversion cost and savings from reduced diversion scenarios: 2018–2035

The distribution of potential savings globally from a 50% reduction in diversions due to on-board emergencies is depicted in Chart 2.

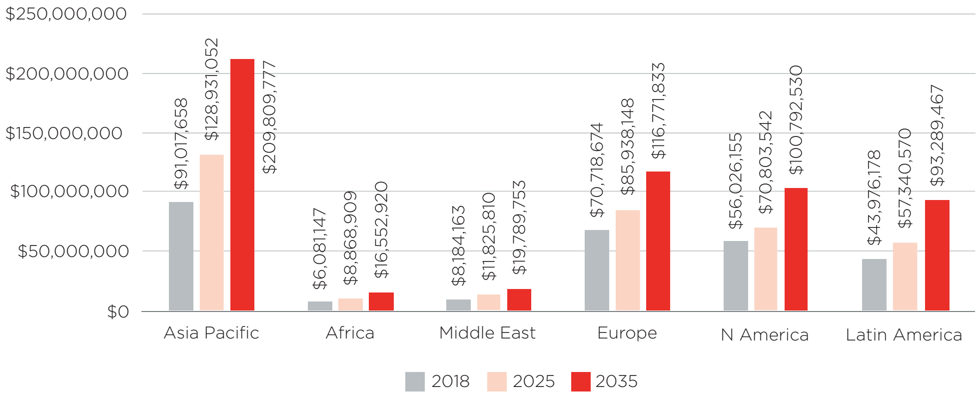

Chart 2: Global distribution of savings for a 50% reduction in emergency diversions – 2018, 2025, 2035

If emergency diversions are reduced through connected telemedicine, the benefits could be significant: a reduction of 75% from current diversions yields a cumulative decrease between 2018–2035 of US$10 billion. A reduction of 50% and 25% could result in a cumulative decrease of US$7 billion and US$3.7 billion respectively. A reduction of 10% can yield a cumulative decrease of US$1.4 billion over this period. Airline managers identified this area as a key target for improvement through a connected aircraft. The savings range highlighted was wide, ranging from 30%–70%, reflecting uncertainty around the benefits that could accrue at the initial phase of connected aircraft penetration.

Other Irregular Operations

The connected aircraft can provide enhanced live cargo monitoring by streaming images and transmitting health indicators if required. This can be delivered directly to other parties, including insurance companies, with premiums in future potentially being defined by the degree of monitoring and surveillance provided. This could be utilised for high-value live cargo such as racehorses.

IP-connectivity can also assist with a silent 'panic alert' that triggers multiple on-board systems such as cameras and microphones, and in the future, potentially with remote pilot override, in the event of a hijack situation.

Disruption Management

A connected aircraft facilitates the two-way utilisation of enhanced data between the aircraft and ground operations to reduce delays and minimise corresponding costs and issues. This encompasses weather data; traffic build-up en route or near the destination airport; and other information that can be utilised to reduce delays. This is of particular relevance to low-cost airlines where turnaround times are critical to on-time departures.

Passenger Compensation

Improved turnarounds and on-time departures reduce passenger compensation costs, such as those stipulated under regulation (EC) No 261/2004 of the European Parliament and of the Council (EU261). These have defined rules for compensation and assistance to passengers in the event of being denied boarding, cancellation or the long delay of flights.[219] EU261 provides compensation from €250–€600, and was recently extended via the UK Court of Appeal[220] to apply to non-EU carriers when present in the EU.[221] Liability occurs if the passenger arrives at their final destination three hours or more later than scheduled, regardless of whether this destination is within the EU.[222]

Over 70% of claims under EU261 are for delayed flights over three hours and 23% for cancelled flights.[223] In 2016, 47% of claims were for €250, 29% were for €600, 19% were for €400, and 5% were for €300.[224] Data on compensation claims under EU261 are disparate, with assessment of available information estimating that the compensation liability was US$3 billion in 2016.[225] Utilising this cost in conjunction with 3.7 billion passengers carried in 2016[226] results in an average per passenger cost of US$0.81. Improved en route efficiency through a connected aircraft could generate a reduction in compensation costs. Table 11 depicts a range of potential savings, with industry discussions indicating that initially, a 10%–15% reduction of delays could occur from a smaller connected aircraft base, growing over time.

Reduction of delays	EU261 Cost	EU261 Saving
10%	$2,700,000,000	$300,000,000
30%	$2,100,000,000	$900,000,000
66%	$1,020,000,000	$1,980,000,000
80%	$600,000,000	$2,400,000,000

Table 11: Estimated savings from reduced delays and cancellations to EU261 claims

Safety and Operations Risk

The advent of high bandwidth, secure satellite connectivity with global coverage, has transformed the role of the aircraft from a singular unit to a node that can broadcast and receive data within the IoT.[227] This delivers both operational and safety benefits, with a former managing director of the National Transportation and Safety Board (NTSB) stating; *"There is absolutely no reason not to have live-streaming data."*[228] Feedback from interviews with industry representatives and airline managers highlighted the concern that to date, although passengers are able to utilise the internet at 35,000 feet, the most valuable information regarding a flight is stored on the same aircraft that could suffer catastrophic failure before data are recovered.[229]

In 2017, ICAO's Global Aeronautical and Distress and Safety System (GADSS) Advisory Group for Autonomous Distress Tracking (ADS) published 27 criteria for areas of improvement for aircraft systems, air traffic services (ATS) and search and rescue (SAR) system operations.[230] This incorporated new Standards and Recommended Practices (SARP). From November 8, 2018, Amendments 39 and 40 to Annex 6 of the Chicago Convention will be effective.[231] Amendment 39 requires an aircraft tracking time interval of 15 minutes for aircraft with a take-off mass of 45,500 kg or more flying oceanic routes, and is recommended for aircraft with a take-off mass of 27,000 kg.[232] Amendment 40 requires aircraft to report their position once every minute if they are in distress, and flight data recordings to be extended to 25 hours.[233]

The connected aircraft can meet these requirements by streaming flight data to a Black Box in the Cloud™ (BBIC) and directly to the OCC and ANSPs for monitoring and preventative action where possible, alerting the relevant areas when an aircraft deviates from its intended flight path. In the business and general aviation sector, the NTSB has advocated Distress Assistance with Real-Time Telemetry (DART), as a relevant tool to reduce the number of corporate and private jet safety incidents. Under DART, an off-duty crew is 'on-call' to assist with flight reporting difficulties, or where the crew is required to address a technical failure inflight, utilising real-time data streamed from the aircraft. In addition to the safety benefits, DART can help operators identify technical issues as early as possible.

Pilot awareness of the aircraft's physical location and altitude is a significant aspect of safe flying.[234] Transmission of real-time data to and from the cockpit enables valuable flight updates, including aircraft telemetry, graphical weather and 3D animated views of the surrounding environment.[235] This improves situational awareness, reducing loss of control and other factors that can cause accidents. It can also provide airlines with a web-based view of their fleet, improving total situational awareness at airline level.[236]

Two short case studies reflect high-profile instances of aircraft loss: Malaysian Airlines Flight MH370 and Air France Flight 447. Inflight connectivity can address a number of factors highlighted by these events, including real-time positional tracking by OCC and ATC; flight system monitoring to alert the flight crew; and a Black Box in the Cloud™ (BBIC) to extract key metrics before any catastrophic event occurs, reducing the requirement for access to the physical asset.

Malaysian Airlines Flight MH370

The disappearance on March 4, 2014 of Malaysian Airlines Flight MH370, a Boeing 777- 200ER, reinforced the significance of knowing an aircraft's accurate location at any time. The aircraft has never been found, despite an extensive search, with the loss of 239 lives. The cost of this event includes a payment to families of US$500 million–US$750 million,[237] in addition to an operating loss incurred by the airline of US$137 million in Q1 2014[238] driven by: a 14% drop in share price between March–May 2014;[239] a 20% drop in market value immediately following the disappearance of the flight;[240] a 60% drop in sales from China;[241] and search costs of US$156m.[242] These suggest a total cost of over US$1 billion. The lack of aircraft data preceding the flight's disappearance highlights the need to maintain remote situational awareness of the fleet, in addition to monitoring indicators that may alert ground control to flight characteristics outside of a defined profile. The use of a BBIC can ensure that key cockpit data, recordings and flight performance metrics are obtained on a continuous or defined basis preceding any event where they are required.

Air France Flight 447

Air France Flight 447 was a scheduled passenger flight from Rio de Janeiro, Brazil, to Paris, France. The Airbus A330 entered an aerodynamic stall from which it did not recover and crashed into the Atlantic Ocean on June 1, 2009, with the loss of all 228 passengers and crew.[243] The Brazilian Navy removed the first major piece of wreckage and two bodies from the sea within five days of the accident, but the initial investigation by France's Bureau d'Enquêtes et d'Analyses pour la Sécurité de l'Aviation Civile (BEA) was hampered.[244] The search for the black box took almost two years, with the flight recorders not recovered from the ocean floor until May 2011.[245] The cost of the search approached US$40m with France and Brazil covering the majority of this,[246] and Air France ordered by the courts to pay US$177,000 per victim, equating to a further US$40m in liability.[247] This resulted in a total cost that approached US$100 million.

> The final report identified pilot error and equipment failure, but was published three years after the crash.[248] This lag resulted in Air France making changes to aircraft pitot tube equipment and maintenance, standard operating procedures and pilot training programmes nearly two years later, after the black box was recovered following an extensive investigation.[249] As with the case of MH370, remote monitoring of the aircraft's key parameters could have aided in advanced warning and diagnostics. The opportunity to rapidly make necessary industry-wide changes was also lost due to the need to physically locate the black box.

These case studies highlight the potential safety benefits of the connected aircraft, including the BBIC concept. A former Chairman of the NTSB highlighted the role that IP connectivity can play: *"Safety is a key benefit that IP can deliver to the plane in operations, and to ATC. This can usher in a new era of real-time tracking, metrics, and exception-engagement that ultimately could avert an emergency or a worse outcome. The benefits are many."*[250] The BBIC can capture the Flight Data Recorder (FDR), Quick Access Recorder (QAR) and the Cockpit Voice Recorder (CVR), with additional or specific data streamed to a ground server when an aircraft is in distress, and combined with other data captured preceding this. Flight data and information obtained inflight in real-time, or polled as required, can also be used to assist investigators in the event of an accident or disappearance without the need to physically locate a black box. Airlines can analyse the data surrounding an accident to subsequently introduce measures from lessons learned. This enables intervention and corrective measures to be rapidly implemented across the industry.

Future Regulations

The introduction of broadband connectivity is occurring in parallel to the development and release of relevant compliance and emerging regulations. These include GADSS compliance for tracking and flight data recovery (via BBIC capability) that have already been covered in this report. In addition, two further areas of relevance are emerging and have been reviewed in this report: ESA's Iris programme for Satellite Communication for Air Traffic Management and Reduced Crew/Autonomous Flight Capability.

Satellite Communication for Air Traffic Management – Iris

Iris is part of the European Space Agency's Advanced Research in Telecommunications Systems (ARTES) programme. It is a new satellite-based communication system for Air Traffic Management (ATM). Iris will enable 4D trajectory management via satellite, for both continental and oceanic airspaces, as a safe and reliable service. Communications will take place via robust links and will ultimately be used by the vast majority of aircraft, complemented with conventional voice communications between pilots and controllers. To achieve this goal, Iris will also develop and validate a new standard for satellite communications that can be used for ATM in any region of the world.[251]

The Single European Sky ATM Research (SESAR) programme is driving an initiative to spur capacity, performance and efficiency of ATM, with Iris providing the satellite communications technology for this programme. This will commence with the delivery of air-to-ground communications for initial 4D trajectory management to manage flight path control in four dimensions: latitude, longitude, altitude and time. The use of 4D trajectory management enables airspace users to plan and fly a scheduled route. This creates predictable target times within agreed time windows, while maintaining safety standards and considering weather conditions.[252]

A major component of the 4D trajectory management concept is Flight and Flow Information for a Collaborative Environment (FF-ICE), which supports trajectory-based operations (TBO) through the exchange and distribution of information, with both the US and the EU harmonised on this approach. This will be introduced in Europe initially and expanded to North America, Asia Pacific and other regions. By 2028, Iris will enable full 4D trajectory management around the world, with data becoming the primary means of communication between controllers and flight crews, while voice communications are used only for specific operations.[253]

Autonomous Flight

The major barrier to autonomous flight capability is cultural, with most passengers today resistant to the concept.[254] Autonomous capability has been operational on military drones for a number of years with considerable experience gained by the armed forces to date.[255] This can facilitate a cross-over into the airline industry where this is possible, but this is unlikely to occur in the near future while passenger resistance to crew reduction exists. There is, however, a history of crew reduction in the cockpit: in the 1960s, many aircraft had a five-member flight crew that included a pilot, co-pilot, flight engineer, navigator and radio operator. This had been reduced to a two-person crew of pilot and co-pilot by the 1980s due to enhanced avionics and greater automation.[256]

Some air transport operators are testing unmanned concepts, including Airbus with its Sagitta initiative, and others including Embraer, Boeing and British Airways.[257] The introduction of autonomous flight is not forecast to occur until 2030, with an interim stage potentially being single-pilot aircraft.[258] This could gradually introduce the concept to passengers, with a connected aircraft providing the step-change required to enable greater degrees of automation, and assisting to establish a business case for autonomous flight. A supporting element for any single-pilot operation is a back-up crew member, highlighted in research by NASA on the feasibility of single-pilot operations: *"The physical redundancy offered by a second pilot could be complemented by trained flight attendants or embedding the functions of remotely-piloted vehicles into cockpit design so a ground-based backup can take over when necessary."*[259]

The global cost saving attributed to pilotless aircraft has been estimated to reach US$35 billion by 2040, achieved through a reduction of one crew member, forecast to reduce costs between 33%–50% in the medium term.[260] This is likely to occur in stages, beginning with commercial pilot reduction from two to one, yielding an estimated US$21 billion in annual savings. This could subsequently be followed by the removal of the remaining pilot, contributing a further US$15 billion in savings annually.[261] The constraints to achieving this are regulatory, cultural and often union-related.[262] The advent of higher bandwidth to the aircraft has already occurred and could facilitate further changes in cockpit resources.

Air Traffic Control Services

Air traffic control encompasses four areas: *Surveillance, Communication, Navigation* and *Future Services and Regulation* as depicted in Figure 8.

Figure 8: Air Traffic Control Services

The connected aircraft is a catalyst in the transformation of the aviation ecosystem. This is particularly the case for surveillance, where initiatives to monitor aircraft, including ATC, are undergoing significant changes. In other cases, IP-enabled, real-time data exchange between aircraft and ground-based monitoring agencies is enabling enhanced route planning and a reduction in separation minima, allowing for airspace and existing facilities to accommodate increasing passenger and aircraft numbers.[263] The benefits of migrating current radar-based systems to satellite-based navigation, automating aircraft position reporting and providing digital communications, are estimated to be worth an estimated saving of US$3 billion.[264]

Surveillance

ATC surveillance is evolving, both spatially and in the technology being utilised. IP mobile satellite communications provides significantly greater speed and capacity for enhanced Automatic Dependent Surveillance Contract (ADS-C) surveillance data, which can translate into cost efficiencies for both air navigation service providers (ANSPs) and operators.

Integrated into ANSP ground automation systems with advanced flight data processing, automated alerting, and decision support tools, ADS-C-enabled surveillance along with Controller-Pilot Data Link Communications (CPDLC) enables an air traffic controller to effectively manage very large airspace sectors and high numbers of aircraft.

The increased performance of ADS-C-over-IP will provide cost efficiencies to operators by enabling further reductions in separation minima from today's ADS-C-enabled ICAO published minima of 23 nautical miles (NM) lateral and 30NM longitudinal, as well as through advanced ATM capabilities supported by ADS-C extended projected profile (EPP) data integrated into ATM systems. These capabilities will enable more flights to achieve their optimal route and flight profiles.

A single air traffic controller can manage airspace accommodating 60 or more aircraft: this is not currently possible in a radar-tactical environment, where a controller must visually distinguish the space between aircraft and can manage a maximum of around 20–25 aircraft.[265] Forecasts to 2030 estimate a requirement of around 140,000 air traffic controllers: a significant increase from the 67,000 employed in 2010.[266] The use of remote towers can assist ATC resources to be deployed more efficiently in combination with the migration of some ATC tasks to the flight crew through the use of a connected aircraft.[267]

Communication

Communications capabilities between pilots and air traffic controllers are a key constraint in terms of reducing separation minima and improving airspace efficiency for oceanic and remote airspace. ICAO and ANSPs can utilise enhanced real-time connectivity to provide rapid communications to the aircraft. This permits air traffic controllers to intervene in order to prevent unsafe situations from occurring. Direct Controller Pilot Communications (DCPC) is a further capability that can support reductions in separation standards while providing greater operational flexibility. ICAO is currently developing new required communications performance standards for CPDLC that can be met by CPDLC-over-IP mobile satellite communications. New standards are also required for satellite voice. Separation minima based on these new communications standards will then be possible.

Reliable, consistent, high-quality data communication is crucial to implementing efficiency and capacity improvements as required by SESAR.[268] VHF VDL Mode 2 is the mandated solution in Europe under Regulation (EC) No29/2009, amended by Implementing Regulation (EU) 2015/310.[269] VDL is a digital radio link used for communication between aircraft and the ground, and is the primary channel for the VHF ground/air sub-system that is used for the Aeronautical Telecommunication Network (ATN).[270] VDL data consists of messages between pilots and Air Traffic Service (ATS) and Aeronautical Administrative Communications (AAC), including route clearances, information between the aircraft and airline, and ACARS messages.[271] A single VDL Mode 2 frequency channel is currently reaching saturation in high density traffic areas: the addition of two to three more channels is unlikely to be sufficient to accommodate the vast increase forecast in data by 2035.[272] In the US, the FAA is assessing an upgrade to its current aviation communication systems and requirements, with the Next Generation Transportation System (NextGen). SESAR and NextGen are currently the two largest aviation modernisation efforts in the world.[273]

Navigation

To fully capitalise on the opportunities presented by connected aircraft, regulatory changes are required to facilitate amendments in areas that are key to enabling dynamic, optimised route planning, while moderating capacity. Changes in this area will be needed to accommodate the continued growth in air traffic over the next two decades and beyond.

Fuel Efficiency

The efficient use of airspace is a long-term aviation goal.[274] The environmental impact of failing to make air transport efficiencies could be high.[275] Aircraft fuel accounts for around 18%–20% of airline operating costs[276] and one third of total expenses in the global airline industry.[277] The industry's CO_2 contribution accounts for around 2.5% of total CO_2 emissions, but the impact per kilogram of high-altitude emissions on climate change is around double that of ground-level emissions.[278] International aviation is responsible for over 60% of total aviation emissions and is the fastest growing segment of the market.[279] With emissions approximately proportional to fuel consumption, additional fuel burn will worsen global CO_2 contribution.[280] In 2012, commercial aircraft emitted about 0.7 billion metric tonnes of CO_2 globally, positioning aircraft CO_2 emissions seventh in a national league table after the total emissions of Germany. Between 2006–2050, these emissions are forecast to triple as air traffic continues to grow.[281]

In contrast, engine technology improvements have enhanced fuel efficiency, with the average fuel burn of new aircraft falling approximately 45% from 1968 to 2014, with a compounded annual reduction rate of 1.3%.[282] Litres per passenger per 100km have halved from eight to four between 1995–2015, and are forecast to shrink to around three litres per passenger by 2025.[283] In 2017, fuel efficiency gains driven by newer aircraft resulted in fuel burn and CO_2 emissions estimated as 1.1% lower than they otherwise would have been, saving US$1.4 billion in additional fuel costs and 9 million tonnes of CO_2.[284] The gains achieved through more efficient engine technology can be rapidly offset by flying inefficient routes. The delays caused by inefficient airspace management in Europe are forecast to have cost the industry over €2.8 billion in 2017, whilst the cost to passengers was €4.9 billion in the year.[285] This equates to an annual cost for Europe of around €8 billion.

Improving fuel efficiency is driven by a number of factors including: demand for travel that drives newer more efficient aircraft designs; technological progress by engine manufacturers and by other participants; and how an aircraft is flown.[286] ICAO has highlighted that while *"technology advances in aircraft have been the major factor in improving the efficiency of air transport. Continued economic growth tied in with air traffic growth necessitates a multi-faceted approach to meeting the challenge".*[287] This multi-faceted approach encompasses modern fuel-efficient aircraft, optimised for load factors, coupled with flying the most efficient flight paths enabled by enhanced technology.[288] Reducing one minute from each of the 38 million annual flights worldwide would result in US$2 billion savings.[289] Optimised flight planning and other efficiencies have been estimated to yield 2%–3% fuel savings per flight, resulting in 3.3 billion–10.1 billion litres saved per annum globally, valued at US$1.3 billion–US$3.9 billion, and a reduction of 8.5 million–25.5 million tonnes of CO_2 annually.[290]

Flight Inefficiency

Flight inefficiency occurs when an aircraft's flight path deviates from its optimum 4D trajectory.[291] It can be assessed using a Flight Inefficiency Metric (FIM) that calculates the difference between the theoretical minimum distance that could be flown between two points and the actual distance flown. This determines the average route extension over the great circle distance and any inefficiency that occurs:[292]

$$\text{Flight Inefficiency Metric (FIM) (\%)} = \frac{\text{Actual-Optimal}}{\text{Optimal}} \times 100\%$$

The influencing factors for optimum fuel burn include:

- Aircraft type
- Weight
- Centre of gravity

Within the direct control of the airline, representing efficient aircraft management operations

- Temperature
- Winds
- Route length
- Operator's cost index[293]

Potential for enhanced connectivity to optimise these elements, combined in some cases with revised processes

The operator's Cost Index is the ratio of time-related costs per minute of flight, relative to the fuel-related costs per kg of fuel burnt. It can be used to assist airlines in reducing operating costs, although is not always fully utilised.[294] The Cost Index selected is entered into the FMS of the aircraft. This varies from one airline to another. The choice of Cost Index affects fuel burn.[295] Industry discussions indicate that flight-optimising software, combined with enhanced connectivity, could potentially result in a 1% fuel reduction per flight. Connectivity could enable this efficiency in several ways:

- Enhancing data in the FMS for the Cost Index selected with first principal, real-time data:
  - The FMS can then re-calculate and re-optimise the route dynamically, using a high sampling frequency but with low data overhead for each;
- Use of the cloud, providing greater processing capability off-plane, then integrating results back into the FMS;
- Enhancing tools for the flight crew such as visualised turbulence data;
- Data profiles can be built up over time and used to enhance a Cost Index;
- Real-time data from one aircraft can be accessed and analysed by operations teams and transmitted across a fleet where relevant to optimise other flights.

The ultimate fuel reduction that an aircraft can achieve is also moderated by congestion, which is managed by ATC and is outside of the airline's control. ATC delays en route can offset the benefits gained by fuel efficiency.

The impact of ATC on flight efficiency is recognised by SESAR, which seeks to meet future capacity and safety needs. *"Currently, flight paths predominantly follow set air corridors that make the route longer than necessary. On arrival at the destination the aircraft may have to circle in a holding pattern or descend in stages while awaiting a landing slot. All of these factors increase fuel consumption,* *pollution and greenhouse gas emissions. Single European Sky ATM Research (SESAR) technology will enable more direct flight paths and smooth descent and climbing, which will eliminate some of the inefficiencies…It will help create a 'paradigm shift', supported by state-of-the-art and innovative technology capable of ensuring the safety, fluidity and sustainability of air transport worldwide over the next 30 years."*[296]

En route fuel consumption is affected by the freedom to fly an optimal route, route design, route operation and ATC intervention.[297] Data obtained for the total horizontal, en route, flight inefficiency for flights in Europe indicate that this is marginally higher than the US: 2.98% versus 2.73% respectively.[298] The mean distance per flight in Europe is approximately 1,600km (1,000 miles),[299] compared to 1,500km (941 miles) in the US.[300] For Europe, this inefficiency equates to almost an extra 29 miles flown, versus 27 miles for the US. For a single aisle aircraft, such as an A320, this equates to around an extra 60 gallons or 227 litres of fuel per segment and an additional annual cost to the European and US airline industries of US$3.8 billion and US$3.5 billion respectively, with 25.4 million and 23.2 million tonnes of additional CO_2 produced.[301]

Industry discussions indicate that enhanced communication between the cockpit and ground crews for a high proportion of the flight could yield up to 2% fuel savings.[302] Results from EU and US data indicate that lateral inefficiency between the two continents is similar, and that average fuel inefficiency is significantly greater than equivalent lateral inefficiency.[303] This equates to 23% more block fuel being burnt on average relative to the theoretical lowest average fuel burn.[304] These inefficiencies are driven by a number of possible causes, including air traffic management, separation requirements and congestion. Interviews indicate that the figure for inefficiency could be 5%–12%. Aircraft engine emissions are directly related to fuel burn, with every kilogram of fuel saved estimated to reduce CO_2 by an estimated 3.16 kg.[305] The total global fuel cost in 2017 was around US$130 billion for 339 billion litres of fuel.[306] Utilising the value of 23% inefficiency, this equates to a cost of US$30 billion per annum and around 77.8 billion litres due to air traffic management, separation and congestion. This inefficiency range (5%–12%) could result in a cost of US$6.5 billion–US$15.5 billion and 16.9 billion–40.6 billion litres of fuel respectively. An inefficiency figure of 1% results in US$1.3 billion in fuel costs per annum and 3.3 billion litres of fuel. The impact of these inefficiencies is summarised in Table 9.

Inefficiency (%)	Inefficiency (US$)	Inefficiency (litres)	Inefficiency (CO_2 tonnes)
23	$30 billion	77.8 billion	196.1 million
12	$15.5 billion	40.6 billion	102.3 million
5	$6.5 billion	16.90 billion	42.6 million
1	$1.3 billion	3.3 billion	8.5 million

Table 9: Inefficiency measures including air traffic management and congestion, 2017

Industry interviews and analysis of secondary data indicate that IP-enabled cockpit communication can yield around 1%–2% saving on average on current global fuel consumption, resulting in savings of US$1.3 billion annually, 3.39 billion litres of fuel and 8.5 million tonnes of CO_2. When other efficiencies highlighted in this report are factored in that can further assist to reduce delays, cancellations and diversions, and enhance preventative maintenance, total annual global savings can be between US$7 billion–US$11 billion annually.

Efficiency and Flight Stages

Connectivity offers the potential to improve performance efficiency across each stage of flight, as depicted in Figure 9. These stages have a disproportionate impact on fuel consumption, which could be optimised with greater integration between ground and air for operations and traffic management.

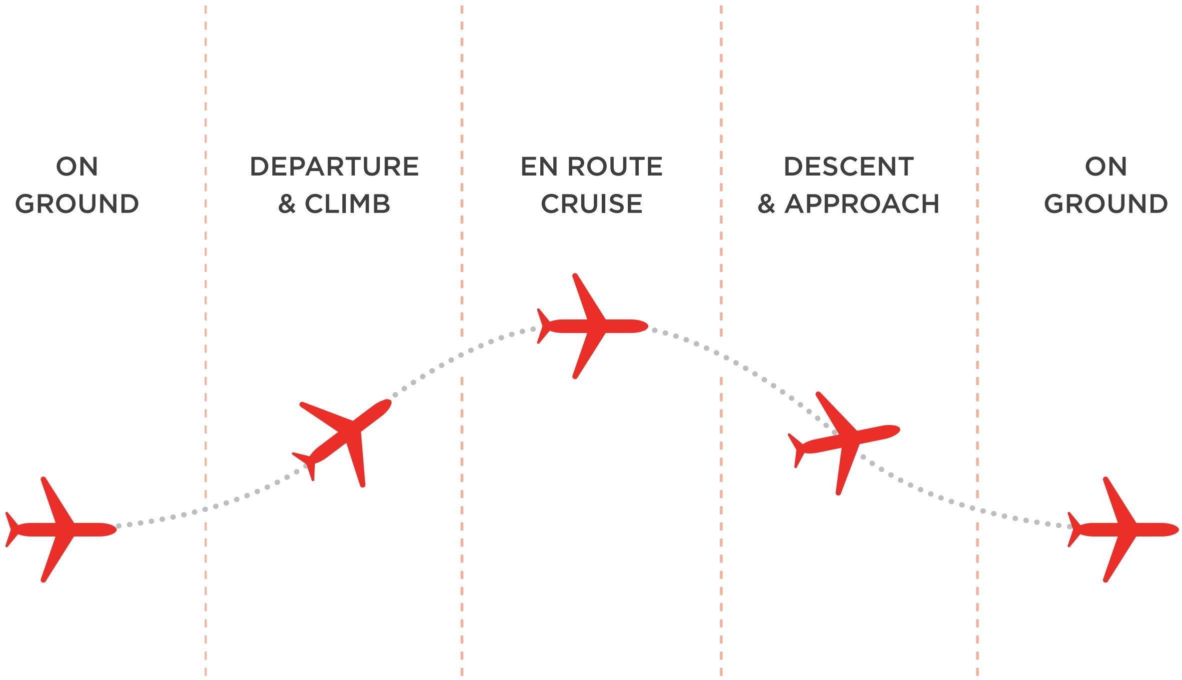

Figure 9: Flight stages

On the Ground Push-Back and Taxi Out

Taxi delays can result in inefficient fuel burn.[307] The ICAO estimate for taxi-out fuel burn defines a constant 7% thrust power setting.[308] Utilising this figure, research indicates that taxi delays consume an average of 1% of total flight fuel.[309] In 2017, using IATA data,[310] this equates to a cost of US$1.3 billion, 3.3 billion litres of fuel and around 150kg of CO_2 emissions.[311] In addition to improving communication on the ground, enhanced connectivity can also bring airport traffic management benefits that can maximise on-time departures occurring.

Departure and Climb

Fuel burn is highest in the initial take off and climb phase; up to 25% of the total fuel consumed during short-haul flights.[312] This segment of the flight requires a short period of high engine thrust without significant opportunities for efficiency. With increasing air traffic congestion, there is often a need to assign aircraft to specific routes and flight levels to maintain separation, resulting in aircraft climbing in a stepped manner separated by periods of level flight. This is not fuel-efficient or emissions-friendly.[313] The selection of an ideal flight path supported by connectivity can assist in both delivering fuel efficiency and reducing CO_2 emissions.

En Route Cruise

During the en route stage, excess fuel burn occurs as a result of two principal factors: approximately 75% is due to inefficiencies including cruise altitude, speed, weather and other factors, with 25% due to en route track extension.[314] The efficiency of a flight is dependent on the fuel efficiency of the plane and other criteria including load factor and flight length.[315] IP aircraft connectivity offers the potential to deliver gains through flight management functions that can optimise routing.[316]

Descent and Approach

Fuel burn is relatively low in a typical descent phase, as the engines are almost idle.[317] This results in relatively low excess fuel burn from track extension during arrival.[318] Optimised ATM, with enhanced connectivity to monitor and communicate route planning, can still deliver efficiencies, including delaying the aircraft's descent from cruise where fuel burn is ideal and clearing the aircraft for landing with minimal holding time.[319] Holding patterns also require engine thrust increases and the maintenance of level flight segments in a non-continuous descent approach, resulting in extra fuel burn that can negate the benefits of optimised flight.[320]

Landing and Taxi

Enhanced connectivity can benefit both ATC and flight crews in optimising traffic flow at the airport and reducing holding periods, ultimately reducing fuel burn and CO_2. Apps can play an increasing role in the management of ground aircraft traffic, while improving situational awareness and fuel use.

Efficiency and Delays

The efficient use of airspace is a long-term aviation goal.[321] With global air traffic forecast to double by 2035,[322] efficient ATM is becoming increasingly challenging. Both Boeing and Airbus are forecasting significant increases in aircraft deliveries by 2035: 45,240[323] and almost 40,000[324] aircraft respectively. This growth has the potential to exacerbate delays without increased efficiency across the air transport ecosystem.[325]

In the US, unnecessary flight delays were estimated to cost US$25 billion in 2016.[326] The average cost of aircraft block time including taxiing and airborne time for US passenger airlines was US$62.55 per minute.[327] Crew costs comprised the largest proportion, at US$21.24 per minute, followed by fuel costs at US$18.44, maintenance at US$12.01, aircraft ownership at US$8.06, and all other costs at US$2.80.[328] Utilising assumptions from the region and extrapolating the analysis to a global context, this could have resulted in delay costs of around US$114 billion globally in 2016.[329] Delays result in:

- Increased costs;
- Lower revenue-amortising time for assets;
- Additional crew requirements, due to the inability to schedule required overlap for incoming-outgoing flights;
- Inefficient maintenance, due to a lack of predictive capability to mitigate delays from 'stranded' aircraft in non-base locations, and others.

Without further ATC efficiencies, wider knock-on effects could ensue:[330]

- An increase in the cost of airport slots;
- Longer flight times, if capacity must be absorbed inflight and in holding patterns;
- Greater operational challenges and knock-on delays, if holding patterns and flight times increase;
- Increased fuel consumption and costs;
- Additional workload for ATC resources;
- Potentially more diversions if fuel emergencies increase;

- Passenger inconvenience through longer flights and related activities.

Eurocontrol data highlight three principal delay categories: reactionary, those caused by airline operations, and other delays:

- Reactionary delays, are the most common delay type caused by the late arrival of an incoming aircraft. These account for around 45% of delays in Europe and average seven minutes per flight.[331] Minimising non-reactionary delays ('primary delays') is critical for an airline in order to minimise subsequent delay for the remainder of the day. Extending turnaround times can reduce reactionary delays, but this runs counter to the practice of decreasing time-on-the-ground in order to schedule a higher number of flights per day.
- Airline operations delays account for around 30% of delays and an average of almost four minutes per flight.[332] These include boarding delays, baggage handling, aircraft cleaning, refuelling and catering, technical defects, documentation issues, late crew boarding or crew shortages.
- The 'other' category, accounting for the remaining 25% of delays, includes flow management on the ground, en route flow management, other airport delays, weather delays and government-related delays.[333] These can average five minutes per flight.[334]

These factors result in an average delay across Europe's 10 million annual flights of around 16 minutes per aircraft for departures and marginally lower for arrivals.[335] For delayed flights, the average delay equates to 30.4 minutes.[336] Delays affect passengers and impact an airline across three cost categories:

- *Hard costs:* These are borne by the airline and encompass re-booking passengers and any compensation required (governed by Regulation (EC) No 261/2004).[337]
- *Soft costs:* These affect the airline through any market share loss due to passenger dissatisfaction.
- *Internalised costs:* These are borne by passengers and include the loss of business due to late arrival, the loss of 'social time', and other costs.

FAA data in 2007 estimated that the direct cost of air transport delays was US$27.2 billion including hard costs of US$8.3 billion; loss of demand/soft costs of US$2.2 billion; and costs to passengers of US$16.7 billion. Adjusting this for inflation and cost of living, the 2017 equivalent is US$32.06 billion, comprised of US$9.7billion, US$2.5 billion and US$19.6 billion respectively.

The potential benefits of a connected aircraft can be combined with other initiatives to mitigate delays:[338]

- Demand and en route capacity management in Europe enforces departure delays to a greater degree than in the US: European flights are twice as likely to be delayed at the gate or on the ground due to en route restrictions.[339] This leads to a lower average delay per flight but a higher share of traffic delayed. Optimising flight operations and connecting the management of ground traffic via satcoms can reduce on-the-ground delays, resulting in more efficient use of gates and faster turnaround times.
- For arrival delays, the proportion of delayed flights at the departure gate or on the ground is higher in the US than in Europe.[340] This results in the length of delay per delayed flight in the US being almost twice as high as the delay per delayed flight in Europe. This delay is generally weather-related, often arising from a small number of high-density, high-impact airports.[341] Connected aircraft can reduce weather-related delays and act as nodes to inform ground operations and other aircraft of weather conditions.[342]

Separation

Flight separation is an area of considerable activity and focus for regulators and airlines. High speed connectivity is transforming air and ground interaction from voice- to data-based.[343] Initiatives such as the SESAR programme are defining the future European Air Traffic Management System (EATMS), significantly increasing data communication.[344] Resulting 4D trajectory management and enhanced digital capabilities enabled via satcom offer the potential to reduce separation minima, lowering fuel use, emissions and enhancing safety,[345] while permitting more controlled arrival times, and increasing airport throughput. This can assist to address the projected saturation of legacy air-to-ground communication systems and resulting congestion.

Different geographies have different operational environments, affected by traffic volume, aircraft equipment and weather.[346] Some areas have particularly high flight congestion, such as the North Atlantic Region. This region is characterised by significantly higher traffic volume than any other oceanic region, with airspace structured in six lanes across the North Atlantic Organised Track System (NAT OTS) that are established twice daily to accommodate the two primary periods of traffic, based on upper winds.[347] Aircraft operating in the NAT OTS are required to be fitted with, and use, CPDLC and ADS-C equipment, which allows more aircraft to use a defined volume of airspace safely and efficiently. This method of communication and surveillance allows aircraft to be managed outside of the range of traditional ground-based VHF radio and radar systems for an extended period.[348]

Future Air Navigation System (FANS)

The standard established by US and Canadian authorities, FANS is used by a high proportion of trans-Atlantic aircraft,[349] permitting CPDLC departure clearance and ADS–C for FANS oceanic routes. These represent a major benefit over high frequency (HF) radio for voice reports including:[350]

- Safety and performance for Communication, Navigation and Surveillance (CNS) and ATM is improved;
- HF traffic is reduced, clearing the channel;
- The often poor quality of HF is not applicable;
- Standardised message set removes any language barrier;
- No impact from solar flares that affect HF.

As initiatives for operational efficiency and airspace optimisation continue to converge, FANS and regulatory and technical initiatives highlight the benefits connectivity can bring for an aircraft and in turn, the wider aviation ecosystem.

Traditional, non-FANS, procedural aircraft separation is influenced by errors in navigation and potential errors in voice communication between the flight crew and air traffic control.[351] The uncertainties of voice position reporting, coupled with the delay inherent in HF voice communications, result in a large area of clear airspace being required between each aircraft as a precautionary measure. This is typically 100NM laterally and 120NM longitudinally.[352] This results in aircraft often operating at less than optimal altitudes and speeds.[353]

Satellite-equipped aircraft with FANS can automatically transmit surveillance reports with a high frequency and accuracy. In addition, more reliable, high-bandwidth satcom enables additional data transfer between the flight crew and the air traffic controller for navigation and surveillance purposes. This reduces the likelihood of errors, permits reduced aircraft separation and ensures more direct routing with no altitude loss when crossing tracks.[354] Aircraft can fly at optimum altitude, burning less fuel, while more flights are accommodated in the same airspace. This is a key requirement in the industry's challenge to meet growing passenger numbers without incurring additional delays, additional fuel burn and higher CO_2 emissions, or resulting in additional infrastructure costs, such as new airport construction.

In addition to enabling cloud-based and other off-aircraft avionics and analytics software, broadband satcom will support trajectory-based operations, enabling some ATC responsibilities to be delegated to flight crews, who will then be responsible for maintaining separation between aircraft.[355]

Approaches to Separation

Reduced separation is advocated by many ANSPs, to enable a greater number of aircraft to fly at their preferred altitudes.[356] This includes ANSPs that manage the NAT OTS *(Nave Canada, Isavia, IAA, NATS UK)* that are seeking reduced lateral separation and have been undertaking minima trials (RLAT) since 2015.[357] Current RLAT tracks are separated by 25NM (1/2 degree), in contrast to 60NM (1 degree).[358] RLAT tracks require suitably equipped aircraft with Required Navigational Performance equipment (RNP4)[359] for oceanic and rural regions and FANS. Unequipped aircraft require larger lateral separation. Activities are occurring to implement a new RLAT phase, with tracks that are separated by 23NM laterally.[360] This will require a high number of FANS aircraft meeting ICAO Performance Based Communication and Surveillance (PBCS) requirements. For FANS/RNP4 aircraft in the NAT OTS, a five minute longitudinal separation minima is possible, although additional longitudinal standards including 10 or 15 minutes are in the NAT.[361] In the New York oceanic Flight Information Region (FIR), the FAA applies ICAO-published 30NM lateral and longitudinal separation between FANS/RNP4 aircraft in some airspace, due to significant congestion and safety concerns.[362] The FAA has additional activities to implement 23 NM lateral separation in all of its oceanic FIRs.[363] Additional published ICAO separation minima include ADS-C climb-descend procedures (CDP), such as ADS-C 15NM or 25NM longitudinal separation between FANS/RNP4 aircraft while climbing/descending through the altitude of another aircraft.[364]

In other regions, approaches to reducing separation minima vary. Some ANSPs have expressed an interest in reducing minima on a dynamic basis, e.g. only as needed, between specific aircraft pairs to better manage points of congestion or impacts from convective weather.[365] For these ANSPs, dynamic use of the tightest minima on an 'as needed' basis, within a normal operation that uses greater separation, enables them to provide the most cost-effective service to airlines. Interviews with ANSP managers indicate that some favour a 20NM lateral separation standard, although they perceive the current 23NM lateral separation as a positive step that can be implemented to improve efficiency in conjunction with the ADS-C longitudinal CDP procedures.

The ICAO Separation and Airspace Safety Panel (SASP) is currently addressing the reduction of separation minima for oceanic airspace enabled by FANS (*CPDLC and ADS-C).* These standards include 20NM longitudinal and are supported by currently available equipment. They require minimal or no additional ANSP investment to modify or optimise existing ground automation, to process increased reporting rates and incorporate the new standards. They require faster ADS-C reporting intervals and new ANSP airspace monitoring requirements to ensure operations and performance are within new established criteria (including occupancy rates, rates and extent of aircraft deviations and communications performance). Existing narrow band services provide this capability, while higher bandwidth will facilitate faster exchanges of information and maintain these standards concurrent to ensuring more stringent PBCS requirements are met.[366]

A connected aircraft offers numerous benefits for separation and other areas:[367]

- ***Safety:*** Near real-time aircraft surveillance can occur with improvements in situational awareness, conflict detection, reaction and resolution, improved flexibility in emergency situations, and the surveillance source being separated from the communications (CPDLC) network sources.
- ***Efficiency:*** 'Domestic-like' flight trajectories can occur in oceanic airspace, enabling more predictable airline cost planning, climb/descend and speed variation to seek wind-push and avoid headwinds, and improved traffic profiles for crossing and opposite direction.
- ***Traffic flow management:*** Improved efficiency of flight planning systems, dispatch, and airline gate-to-gate management.

These benefits can result in reduced fuel and greenhouse gas emissions.[368] Trials indicate that for the 4,000 annual flights in the oceanic region per annum, US$0.4 billion in fuel savings can occur through the use of connected satcoms for the fuel climb stage, with a resulting reduction of 1.15 million tonnes of CO_2.[369] This equates to fuel savings of US$485 per flight, and a reduction of 1.15 tonnes of CO_2 per flight. If connected aircraft use was widespread in 2017 at 90%,[370] the potential savings could have been US$16 billion. If penetration had been 50%, the saving could have been US$8.9 billion. By 2035, this is forecast to increase to US$32 billion and US$17.9 with 90% and 50% aircraft penetration respectively as depicted in Table 12.[371] It is not possible at this time to narrow the potential saving, with interviews indicating that this will emerge following more widespread adoption of connected aircraft.

Fuel saved/flight	$485	
CO_2 saved/flight	1.27 tonnes	
Annual flights est., 2017	36,800,000	
Annual flights est., 2035	73,861,573	
Savings p.a. & Satcom adoption	**90%**	**50%**
Fuel saved 2017	$16,074,264,425	$8,930,146,903
CO_2 saved 2017	42,206,018	23,447,788
Fuel saved 2035	$32,262,783,950	$17,923,768,861
CO_2 saved 2035	84,712,034	47,062,241

Table 12: Climb-stage benefit estimate of satcom (ADS-B) globally in 2017 and 2035

By 2035, the annual benefits are forecast to be US$32 billion and US$17 billion respectively for fuel saving and 84 million and 47 million tonnes of CO_2. The climb phase represents 8%–15% of total time for a medium-long haul flight, whilst in short haul flight (1–1.5 hours), it represents around one-third of the total time[372] and as much as 25% of the total fuel consumed.[373] The use of satcoms during the climb phase can have significant cumulative benefits in reducing both fuel and CO_2.

Future Services: Moving Beyond 'Simple Satcoms'

Oceanic airspace is an example of procedurally controlled airspace, in contrast to radar controlled airspace (ATS surveillance). The introduction of advanced air-to-ground connectivity throughout a flight eliminates the 'black spots' inherent with radar controlled traffic and provides accurate and reliable position data through CPDLC communications, satellite voice communications, and the evolution of ANSP ground automation systems that incorporate information, such as from FANS. This permits the application of separation rules that enhance current standards and, in particular, reduce separation, where radar control does not exist, and/or where radar controlled minima can be reduced.

Advanced satcom connectivity represents the step change in aircraft operations required to accommodate passenger growth. Eurocontrol estimates that air traffic within, to, and from Europe will be limited by capacity at airports, with 5%–19% of demand (0.7–5 million flights) unable to be accommodated by 2030, and 34 airports estimated to reach over 150,000 departures per year, with this figure occurring in seven European airports today:[374] *"Congested airports create pressure on the flow of operations in the network and will exacerbate delays. In addition to unaccommodated demand, airport capacity constraints have an effect on the flow of operations in the network. In particular, it will be more vulnerable to delays that will propagate more rapidly and widely and with more restrictions at the airports and fewer opportunities to recover will stay longer in the system."*[375]

With improvements in aircraft navigation performance, satellite tracking and communication and ANSP automation systems, procedural separation minima continue to be reduced, improving operational flexibility in the process. The first stage of benefits of satellite communications over oceanic regions has resulted in an estimated US$3 billion in savings between 2001–2016 and longitudinal separation reduced over three-fold from 100NM to 30NM, with the resulting capacity increase valued at US$890 million.[376] The advent of IP-based applications and a connected aircraft facilitates satcom-driven flight management that can extend these benefits further into continental areas.

Broadband communication with the cockpit improves the performance of flight tracking and communications capabilities, in addition to providing the potential to reduce separation.[377] Enhanced connectivity also facilitates the integration of flight information into ANSP traffic flow management tools that manage airspace demand and provide tactical information to pilots and operators.[378] Early and accurate information is critical to traffic management: connectivity improves efficiency through the provision of more accurate situational awareness to the cockpit, including real-time weather, special use airspace and conflicting traffic.[379] This information can assist pilots and operators to plan potential route changes for a more efficient flight profile, and eliminate options that may not be optimal or are unlikely to be approved by ATC.

Benefits to Safety

ANSPs can utilise enhanced, real-time connectivity to provide rapid communications to the aircraft. This permits air traffic controllers to intervene in order to prevent unsafe situations from occurring. DCPC is a further capability that can support reductions in separation standards while providing greater operational flexibility.[380] Industry discussions indicate that although it is challenging to demonstrate a business case for oceanic separation standards that are below 23NM lateral and 20NM longitudinal, operators are seeking greater flexibility in providing routings and permitting user-preferred routes, in contrast to fixed ANSP-developed routes.

The use of advanced satellite communications can bring benefits while amending existing practices to improve security.[381] This is increasingly important in a cyber-centric environment:

- The current ground-to-air dial-up latency could be improved through broadband connectivity. The most significant contributing factor to increased latency is a security requirement for two-stage dial-up.[382] This requirement can be removed through more advanced, secure broadband connectivity to the aircraft. A review and possible amendment of some SARPs and guidance materials related to satellite voice security could also ensue by ICAO and regulating bodies.[383]
- Broadband to the aircraft provides a Voice-over-IP (VoIP) channel that offers capabilities, including latency, comparable to VHF. ICAO operational concepts, SARPs and guidance materials are needed to enable globally harmonised adoption and incorporation into new separation minima.

In addition to these step changes, operators and some ANSPs are progressing on the approval of satellite communications as Long Range Communications Systems (LRCS).[384] Satvoice is defined within ICAO Required Communication Performance 400 (RCP 400): *"RCP 400 would be used for controller intervention capability supporting separation assurance in current environments where separations are greater than 30/30 and alternative technologies are planned for providing normal means of communication."*[385] This would permit satellite communications (data and voice) to be used for routine ATS communications, rather than as a back-up for HF. Voice will migrate from being a control means to being a time-critical, non-routine and emergency tool, with the majority of ATC instructions being issued by data link.[386] The benefits of these combined initiatives are particularly evident in the case of oceanic flights, where aircraft are required to carry two LRCSs, resulting in two sets of HF equipment and the corresponding weight of each.[387] If satcoms is designated as an LRCS (a requirement of RCP 400), operators with satcom-equipped aircraft can remove one set of HF equipment, saving fuel and maintenance expenses.[388] For safety reasons, voice and data will continue to be separated, but voice will migrate from analogue to digital. Operations using 4D trajectories will facilitate the use of multiple arrival times, traffic synchronisation, and dynamic demand and capacity balancing for traffic flow, with negotiated trajectories leading to fewer interventions from controllers.[389]

Airline managers continuously seek to improve operating cost efficiency.[390] In the process, airlines often bear the cost for new services, including reducing separation and enhancing efficiency through optimal route flying.[391] Over 90% of oceanic commercial transport aircraft are currently equipped with FANS,[392] representing a significant investment in improving navigational performance and optimising routes. This research indicates a concern reflected by many airlines that airspace rules and operating concepts do not yet fully leverage their current investments to maximise efficiency benefits. As a result, the connected aircraft may currently be racing faster towards this end than some other elements in the digital aviation ecosystem. As regulatory and other industry changes catch up, airlines that have invested in connectivity will be well placed to capitalise on their experience and gain a multi-tiered return on their investment.

Conclusion

This research highlights a diverse range of benefits that could accrue from airlines' investment in connected operations. These include economies in fuel consumption, a reduction in delays and improved on-time departures, innovations in maintenance processes, fleet utilisation efficiencies, safety enhancements and others. Together, these are forecast to yield annual savings of up to US$14.9 billion globally by 2035: approximately 2% of the total cost of airline operations today.

This forecast reflects the assumption that widespread adoption of next generation satcom connectivity services will usher in the era of the connected aircraft. In addition, the research assumes that the potential benefits that can ensue are underpinned by a rapid growth in IP-enabled applications, and that these will be reflected in the continued digitalisation of operations processes on the ground. Obtaining system-wide benefits will require a coordinated approach by airlines, service providers, air traffic management organisations, regulators and others. It is likely that a lagged scenario will occur between the current rapid pace of industry innovation and the slower development and implementation of legislation and standards.

Until recently, the business case for connectivity has been largely based on assessing incremental revenue alone. Interviews indicate that a growing number of airlines are increasingly reviewing a wider context that encompasses both operational savings and ancillary gains. These two areas are not mutually exclusive: the opportunity to monetise passengers provides a parallel springboard for airlines to capitalise on the operational benefits available. They are both elements of the wider digital transformation occurring in the aviation industry that is end-to-end, commencing with initial contact with the passenger and extending beyond the aircraft's arrival at the destination gate.

By 2035, the forecast doubling of annual passengers and aircraft will create both challenges and opportunities. The IP-enabled aircraft is an integral step towards addressing both of these and facilitating efficiencies and benefits. Without it, the industry may be constrained by the limitations of finite airspace and a growing environmental agenda.

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Commissioned via LSE Consulting