Department for Transport

Operational Efficiency Analysis

Document type

Report

Publication date

April 2025

Version

FINAL

Contents

1 Summary

This research, commissioned by the Department for Transport (DfT), explores the potential of operational efficiency measures (through sustainable practices, both on-ground and in-flight) in reducing fuel consumption in flights, thereby lowering CO2 emissions. Conducted over an eight-week period, the study utilizes a route-level analysis to examine varying scenarios for improving operational efficiency between 2025 and 2080. The research is part of a program funded by the Department of Energy Security and Net Zero (DESNZ).

1.1 Research Tasks

The analysis on fuel burn was conducted for the 3259 airport pairs (comprised of 35 origin airports and 103 destination airports) provided by the DfT. For each pair, 4 scenarios were developed for every year between 2025 and 2080. The research undertaken comprised three tasks:

1. Identifying the maximum technical limit of key operational efficiency measures to reduce fuel burn and hence CO2 emissions

A bucketing approach was adopted to avoid double counting measures targeting the same inefficiency, for example single engine taxiing and electric tugs. The five main buckets were:

- **Air traffic management (ATM)** - This bucket concerns the development and evolution of systems which coordinate the movement of aircraft in airspace. Operational efficiency improvements stem from maximizing airspace utilization and increased cooperation between airlines and air traffic controllers in order to achieve more efficient flight paths (referred to as 4D trajectory management).
- **Auxiliary power unit (APU)** - This bucket examines the impact of APU shutdown. APUs are small gas turbines mounted at the back of most aircraft which provide electrical power and bleed air for air conditioning during ground operations. Mitigations here involve replacing APU usage with ground power units (GPUs) and pre-conditioned air (PCA) units.
- **Drag Reduction** - This bucket examines the impact of drag-reduction mechanisms through the use of measures such as formation flight.
- **Taxiing** - This bucket analyses the impact of measures which can be implemented in order to reduce fuel consumption from taxiing operations. Measures include single engine taxiing, electric tugs and electric taxi.
- **Mass reduction** - This bucket looks into the fuel burn impact of reducing the cabin mass of existing aircraft, by making constituent elements of cabins (such as seats, carpets, stowage bins etc.) more lightweight.

All these buckets were combined into total fuel savings in the technical limit scenario.

Note: Drag Reduction, which may entail the use of measures like retrofit winglets and formation flight, is fundamentally an aerodynamic concept which aims to improve fuel efficiency by achieving a reduction in induced drag. While measures such as formation flight may be facilitated through and require adjustments from air traffic management to ensure safe coordination and routing for multi-aircraft formation configurations, it remains a physics-based measure which excludes it from the ATM bucket which is operations and systems-based.

To see a detailed list of which measures are within the scope of this work, visit the scope section of the documentation.

2. Developing scenarios for the projected future of operational efficiency measures between 2025 and 2080

Four scenarios were developed: (i) Pessimistic, (ii) Expected, (iii) Optimistic and (iv) Technical Limit. The different scenarios, as the names suggest, reflect different levels of ambition. Individual justifications for the rollout and efficacy are provided in the detailed documentation pages for each measure.

In the pessimistic scenario, improvements are minimal or non-existent due to regulatory, financial or technological barriers. The expected scenario reflects a likely pathway given current policy and industry trends. It represents a consensus view of the projections and efficacies shown within the existing literature. The optimistic scenario assumes faster and higher adoption rates for measures as well as rapid technological progress driven by stronger regulatory support. The technical limit represents the absolute maximum fuel savings possible without consideration of the aforementioned hurdles with full optimization of all the technological and operational factors.

3. Costing the different operational measures

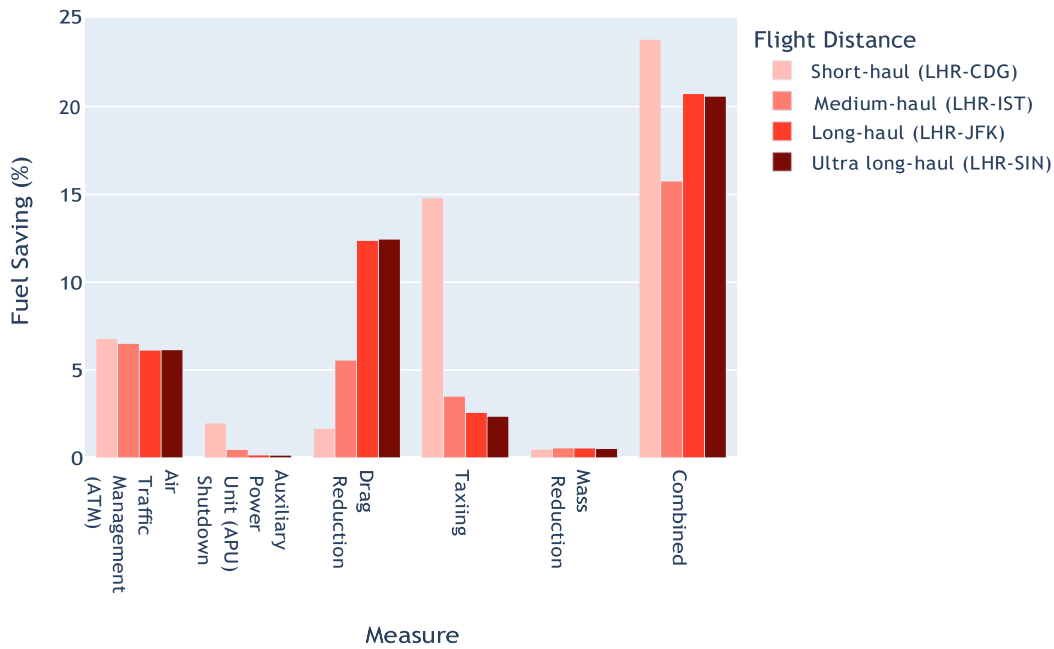
These are presented as total investment costs for a global implementation of the operational measures.

1.2 Key Findings

1.2.1 Maximum Technical Limit for different Categories of Flight

The figure below shows the technical limit for four categories of flight: ultra short-haul (300-1000 km), medium-haul (1000-4000 km), long-haul (4000-8000 km), and ultra long-haul (> 8000 km). Representative routes were selected according to the highest passenger traffic as per CAA data[1] from November 2024.

Figure 1- Maximum Technical Limits for Fuel Savings



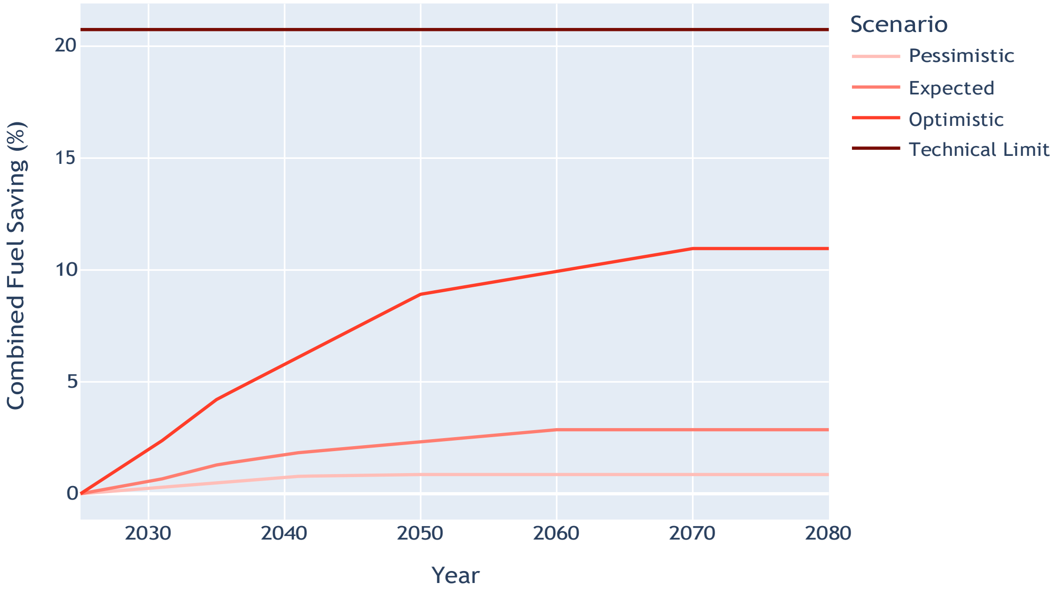
It can be observed that the technical limit for the ultra short-haul flights is higher than the other flight categories. The taxi phase, which forms comparatively a larger proportion of the overall flight, is a significant contributor towards greater fuel savings for short-haul flights. The impact of electric tugs for taxiing, and other on-ground measures like APU shutdown, reduces significantly for other flight categories. In contrast, the impact of in-flight measures including drag-reduction through formation flying and ATM improvements as the flight distance increases.

Technical limits represent the theoretical maximum fuel savings that can be achieved through an operational measure. In the case of "Drag" in the figure, where the technical limit is highlighted as roughly 13% for long-haul flights, this represents a highly optimistic case of a three-aircraft configuration for formation flight, including consideration of multi-airline alliances and coordination. For some of the measures, the technical limit is a sudden jump and this refers to the difference between optimistic estimates of fuel savings (potentially realizable) and theoretical maximum savings which are based on ideal conditions and may not always reflect real-world complexities such as weather, human factors, aircraft limitations and safety.

1.2.2 Scenario Modelling

The figure below shows the four scenarios of combined operational savings for a representative airport-pair (LHR-JFK).

Figure 2: Combined Fuel Savings for LHR-JFK

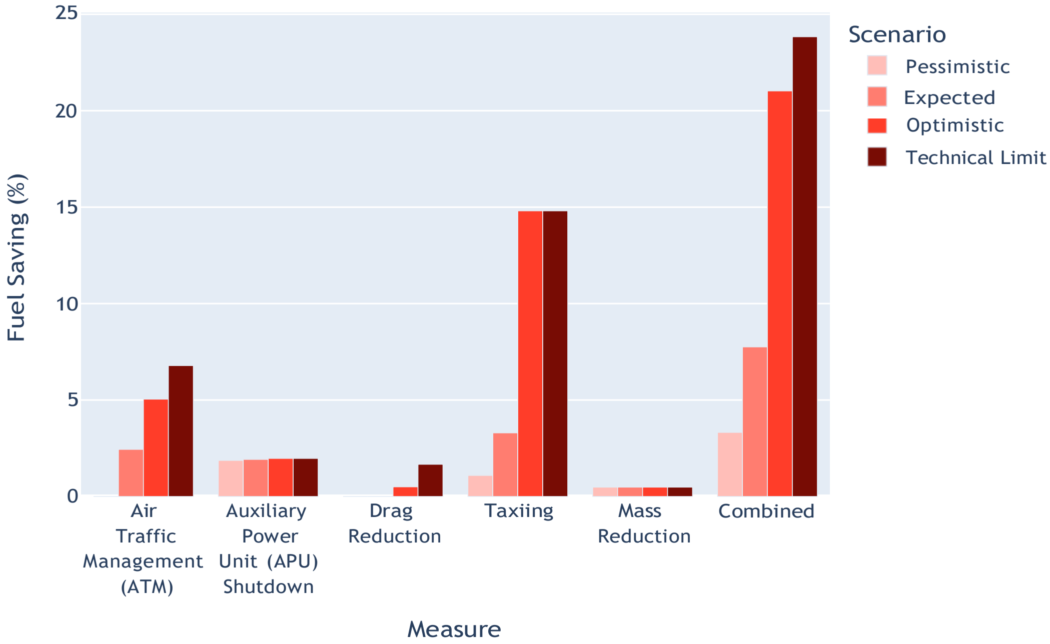


As shown, the technical limit (Scenario 4) is flat across all years, which is expected as per the definition of the technical limit provided above. As shown, all scenarios, except scenario 3, plateau around the year 2060. This is expected given that analysis stops at 2060, due to the lack of evidence and challenge of projecting further than this point in the future. Scenario 3 extends until 2070 because it incorporates formation flying which is a highly ambitious operational measure that will likely require an extended implementation period. It can be noticed that the gap between the high-ambition and medium scenarios is greater than that between the medium and low-ambition scenarios. The reason for this is that it was assumed in the analysis that formation flying, which has significant theoretical potential, is only possible in a high ambition scenario. In the case of taxiing, high efficacy measures such as electric tugs dominate in Scenarios 3 and 4, whereas less optimistic scenarios assume some levels of single engine taxiing which has lower efficacy.

1.2.3 Short-Haul vs Long-Haul

The following figures show the breakdown of the different operational measures under different scenarios for two representative routes, one of which is short-haul (LHR-CDG) and the other is long-haul (LHR-JFK). The aim is to show how the different routes are being impacted by the measures differently under the different scenarios.

Figure 3: Fuel Savings for LHR-CDG in 2080

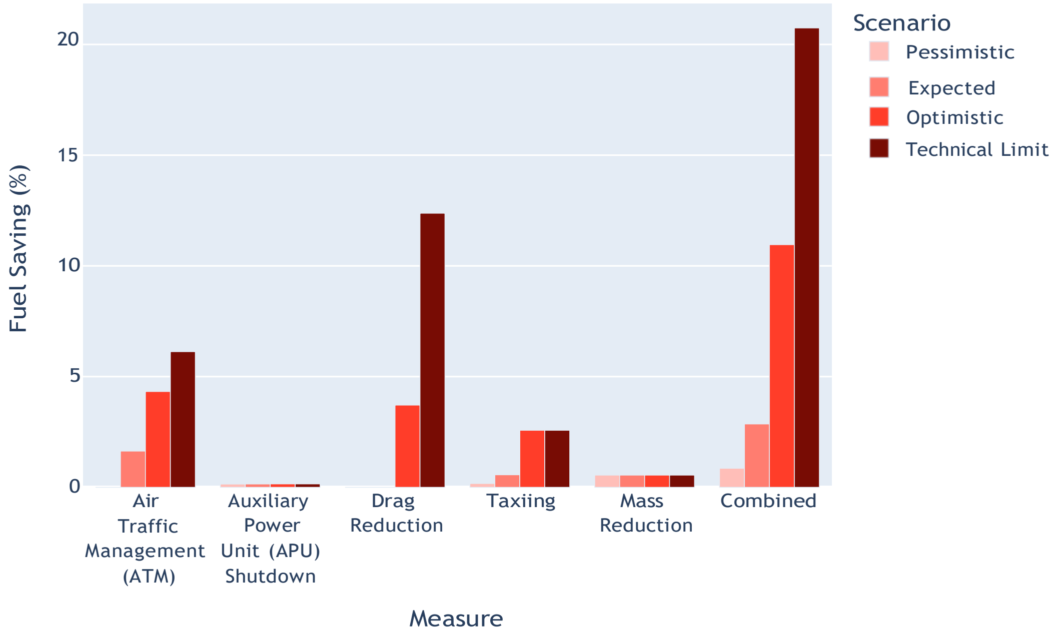


The short-haul analysis highlights the importance of on-ground measures in emission mitigation. In the pessimistic scenario, it is observed that APU shutdown yields the greatest fuel savings, outcompeting the likes of taxiing mitigations which go on to dominate fuel savings in more optimistic scenarios. The reason for this is that APU shutdown, facilitated by the use of pre-conditioned air units and electric ground power, comes with high efficacy (the ability to contribute to large reductions in fuel consumption) and moderate immediate rollout, given that it is actively being implemented as a measure today at airports such as Heathrow and Frankfurt airports. Single-engine taxiing, on the other hand, is assumed for the pessimistic case. Given operational constraints (governed by weather, airport geometry and pilot training) as well as a lower efficacy, single-engine taxiing thus does not contribute to as much fuel saving in comparison. In the optimistic case, taxiing measures through the use of electric tugs yield the greatest savings by far, given high rollout and efficacy, mitigating for the relative large proportion of fuel which is consumed through taxi-in and taxi-out operations in short-haul flights.

For these flights, the highest impact (in the optimistic scenario) comes from taxiing measures, but mostly electric tugs. Single engine taxiing, however, which is used in Scenario 1, does not yield the largest impact.

Note: It is observed that for taxiing operational measures, the fuel savings are shown to be the same in the optimistic and technical limit scenarios. This is because reducing the taxi emissions to zero is not just technically possible, it is realistically achievable given that it only requires a moderate number of electric tugs and decarbonized electrical grids by 2080.

Figure 4: Fuel Savings for LHR-JFK in 2080



The long-haul analysis highlights the need for ATM modernization in order to be able to realize substantial fuel savings. In the optimistic scenario, ATM improvements account for the highest fuel savings, followed closely by drag reduction measures such as formation flying. However, the integration of formation flight into aviation operations requires modernization within ATM systems to support advanced air traffic coordination and support for maintaining refined separation standards. In the pessimistic scenario, only ground-based measures and mass reduction provide fuel savings, although very small (at below 1%).

Note: It should be noted that the fuel savings in the charts for the 2080 analysis assume a baseline where there are no further advancements in fuel efficiency or new aircraft technologies other than those available today. The counterfactual therefore does not account for engine performance improvement, adoption of zero-emission flight technologies such as battery-electric or hydrogen aircraft.

References

[1] *UK airport data November 2024 | Civil Aviation Authority*. URL: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2024/november-2024/ (visited on 02/01/2025).

2 Introduction

This document provides comprehensive documentation of the analysis undertaken by the Aviation Impact Accelerator to support the UK Government Department for Transport. The work described herein reflects a significant effort to ensure transparency in the methodologies and assumptions used throughout the process.

The document is structured into seven sections:

Modeling Summary: This section summarize the body of work undertaken during the sprint and the key results.

Scope: This section outlines the scope of work undertaken, including justifications for why certain aspects were not included.

Overarching Assumptions: This section provides detailed documentation for assumptions and scenarios that underpin all aspects of the analysis.

Briefing Notes: These notes summarize key insights generated in response to government queries. Each note addresses a distinct question, providing a concise synthesis of findings and their implications. This section is designed to support policy development by providing a greater understanding of the subject matter.

Great Circle Distance Uplifts: This section provides detailed documentation of the analytical framework and modeling inputs that underpin the analysis for the determination of the GCD uplift factors. It includes descriptions of data sources, key assumptions, methodologies, and references.

Operational Measures: This section provides detailed documentation for modeling concerning operational measures.

Ticket Costs: This section provides detailed documentation for the methodology behind ticket costing.

This document is intended to serve as both a record of the analysis performed and a resource for stakeholders seeking to understand the evidence base behind the Aviation Impact Accelerator's modeling results and analysis.

2.1 Disclaimer

This document is published by the Aviation Impact Accelerator (AIA), an initiative led by the University of Cambridge. The AIA aims to collect evidence and knowledge by engaging a wide range of stakeholders. The recommendations and opinions expressed in this document represent the collective input of the AIA and do not necessarily reflect the official position of the University of Cambridge, the Cambridge Institute for Sustainability Leadership, or the Department of Engineering at the University of Cambridge, or those of the AIA's funders, partners and collaborators; they are provided for informational purposes only and are not intended as definitive guidance or as an endorsement or support for any specific action. The AIA accepts no liability for any actions taken or decisions made based on the contents of this document. In accordance with the terms of the GFA, all intellectual property rights in this document belong to the AIA. Save to the extent permitted under the GFA, this document may not be published, or any additions or modifications made to its content, without the prior written consent of the AIA.

3 Software Methodology

The AIA conducts analysis with full reproducibility and auditability in mind. All data and insights are produced in an automated and versioned manner meaning that in the future it is possible for us to explain the underlying data sources, assumptions, references, and calculations used to produce each result.

The AIA's data and modeling software packages are the foundation of this approach. These are software packages that encompass the data and models required to create a systems model for a specific system. Examples include the packages for data on resource availability (aia-data-resource) and packages implementing models of the fuel production system (aia-model-fuels) or distribution systems (aia-model-distribution). The per-system packages are written so that adjacent systems can be combined to create systems-of-system models that can themselves be used in analyses. Each of these packages implements models developed and refined by the AIA over multiple years as new data, insights, and methodologies emerge. This ongoing refinement approach ensures that the models remain robust, accurate, and in alignment with the latest developments within both academia and industry. Thus, model-derived data and insights may change incrementally over time, reflecting these iterative improvements. These models and their implementations have been validated by the AIA and the codebases are fully tested. Each model's documentation includes details about all necessary data sources, assumptions, references, and calculations. All documentation is sufficiently detailed such that it can be used in isolation to implement any of these models from scratch. The AIA's data and modeling software packages are source controlled and versioned upon release. This means that when they are leveraged by downstream analysis, that analysis is pinned to specific versions of the data and models, allowing for full reproducibility and auditability.

The AIA creates a new source-controlled repository for each new analysis project. Source control (alternatively called version control) preserves the history of changes to the codebase along with descriptions of why the changes were made. If the results produced by analyses change between versions then the version control allows for the reasons behind these changes to be interrogated and explained. These repositories contain several components including the scripts and supporting code responsible for running the analysis; the frozen environment (all software dependencies and their versions) used to run the analysis; and full documentation describing the analysis being conducted, all data and dependencies used, write-ups of insights generated by the analysis, and anything else specific to the analysis. Any script that runs a component of the analysis generates artifacts. Artifacts can be anything from interactive graphics to datasets to written insights. Datasets are generated dynamically by running the analysis scripts with varied input configurations, with these input parametrizations being immortalized in the repository's version history. Following an analysis run, the resulting data is written to an analysis-specific database. These databases are marked as read-only so that their data cannot be accidentally modified after their creation.

Analyses are run in an automated fashion in the cloud using a continuous deployment (CD) pipeline. The pipeline run is triggered by a versioned release of the analysis repository. This release starts the pipeline which runs the analysis scripts to produce all of the analysis artifacts and then finally stores the artifacts in a read-only cloud storage bucket for their safe indefinite storage. These versioned artifacts, like datasets, can then be distributed as required for their use by downstream analyses, either by the AIA or others.

The final component of an analysis run is the production of the associated versioned documentation. This documentation exists as both a full interactive website and as a static PDF report. For both mediums, the documentation contains all of the information specific to the associated version of the analysis. This documentation is also produced in an automated fashion as part of the CD pipeline run.

4 Scope

An initial list of measures was provided by the DfT. Each of these measures were considered, along with the AIA's own suggestions to create a scope for the measures included in this analysis.

Note: This section refers to **modeled**, **considered** and **unconsidered** measures.
Modeled measures refer to metrics which have been specifically been quantified or predicted within literature. The impact of the measure can thus be isolated.

Considered measures are typically part of a broader set of factors which have been taken into account during analysis but their individual impact has not been specifically quantified. In other words, the AIA recognizes them as being influential but in conjunction with other considered measures, making it difficult to be able to pinpoint their direct impact. They are thus considered in a holistic sense rather than being the sole focus. An example would be the use of Artificial Intelligence which could augment air traffic management improvements but its direct impact is difficult to determine with the current research gaps within the field. Some of these measures have been qualitatively discussed further through briefing notes but are not modeled due to their limited impact or the reasons outlined previously.

Unconsidered measures are deemed to be out-of-scope for this body of work.

4.1 Modeled Measures

Interventions	Explanation	Comment
Trajectory optimization	Determining the most efficient path for an aircraft to follow, minimizing fuel consumption	See 4D Trajectory Management
Formation flying	Coordinating flight of multiple aircraft in specific configurations to reduce induced drag for reduced fuel consumption	See Formation Flying
Reduced engine taxi	Using lower engine thrust setting or fewer engines for taxiing operations	See Single Engine Taxi
Lightweight cabin equipment	Use of lighter components within aircraft, e.g. seats and overhead bins, to reduce the overall weight of aircraft and improve fuel efficiency	See Mass Reduction
Continuous climb operations (CCO) and continuous descent operations (CDO)	Optimization of climb and descent profiles by maintaining continuous trajectories without any leveling off to intermediate altitudes	See Continuous Climb / Descent
Electric ground support equipment (GSE)	Use of electrically-powered machinery, such as electric ground power units, to limit auxiliary power unit operation and thus reducing fuel consumption	See Auxiliary Power Unit
Pre-condition air systems while on the ground (PCA)	Use of pre-conditioned air to prevent use of auxiliary power units for bleed air to reduce fuel consumption	See Auxiliary Power Unit
Electric or assisted taxi	Use of electrically-powered systems or vehicles to move an aircraft during taxiing operations	See Electric Tug and Electric Taxi

4.2 Considered Measures

Interventions	Explanation	Comment
Wingtip device retrofit	Use of aerodynamic modification to aircraft wingtips to reduce drag for increased fuel efficiency	See Wingtip Devices briefing note
Load maximization	Optimizing the amount of cargo/passengers an aircraft can carry for increased operational efficiency, reducing emissions per passenger-kilometer	See Load Maximization briefing note
Airline flight planning optimization	Strategic planning and optimization of flight routes	Impact included within ATM measures.
Free route airspace	Aircraft are not constrained by fixed airways but rather can fly directly between predefined entry and exit points for more efficient routing	Impact included within ATM measures.
Real-time data for pilots	Continuous stream of information provided to pilots during flights to help them make informed decisions on routing	Impact included within ATM measures.
Artificial Intelligence (AI)	Can analyze flight data to augment flight route optimization and dynamic scheduling	Impact included within ATM measures.
Pilot training	Training focused on specialized techniques to ensure safety and precision to facilitate measures which require greater pilot skill and precision to implement, e.g. formation flying or single engine taxiing	Impact included within CCO, CDO, formation flying and reduced engine taxiing measures.
Renewable energy	Use of renewable resources/energy to reduce greenhouse gas emissions	Energy source for electric tugs, electric GSE, PCA assumed renewable.
Data and analytics	Data resulting from flight operations taken from airlines, airports and other aviation stakeholders	Supports most measures but is not in itself a measure.

4.3 Unconsidered Measures

Interventions	Explanation	Comment
Whole life approach to aircraft and operations	Optimization of every stage of an aircraft's lifecycle: from design and operation to decommissioning	Non-flight emissions are out of scope.
Maintenance scheduling	Planning and optimizing inspections, repairs and servicing of aircraft to ensure optimal performance and slow degradation	Lack of data, small performance benefit.
Electric / hybrid propulsion	Use of electric motors combined with traditional engines to power aircraft and reduce fuel consumption	Aircraft fleet changes are out of scope.
Non-conventional aircraft configurations	Use of innovative aircraft design to improve aerodynamics for increased fuel efficiency	Aircraft fleet changes are out of scope.
Hydrogen propulsion	Use of hydrogen to power aircraft to eliminate tail-pipe CO_2 emissions	Aircraft fleet changes are out of scope.
Remote towers	Air traffic controllers are able to manage airport operations from a distant location	No significant fuel burn impact.
In-flight refueling	Process of transferring fuel from one aircraft to another during flight, allowing extended flight range	Impractical, potential benefit for small minority of flights
Building energy efficiency improvements	Implementing measures which allow better insulation, energy-efficient lighting and heating/cooling systems within airport buildings	Non-flight emissions are out of scope.
Stand design	Often included with apron optimization for efficient space utilization with the airport boundary	Non-flight emissions are out of scope.

5 Overarching Assumptions

5.1 Overarching Assumptions for Representative Airports

This document aims to outline the key assumptions pertaining to representative airports that were made for the analysis undertaken in this body of work.

5.1.1 IATA codes mapping to DfT region codes

The 5XXX series of DfT airport codes maps to geographic regions rather than specific airports. The analysis conducted by the AIA assumes specific departure and arrival coordinates for each journey, thus there was a need to map geographic region codes to airport IATA codes.

Methodology

The Civil Aviation Authority (CAA) collates data on both domestic and international air passenger traffic route analysis[1]. The AIA analyzed this CAA dataset for November 2024. The total passenger traffic during the specified period across UK airports was aggregated to map region codes to the airport with the highest UK traffic.

Summary Table

DfT Code	Region	IATA Code	Airport Name
5001	US East	JFK	John F. Kennedy International Airport
5002	US West	LAX	Los Angeles International Airport
5003	Canada East	YYZ	Toronto Pearson International Airport
5004	Canada West	YVR	Vancouver International Airport
5005	Caribbean	BGI	Grantley Adams International Airport
5006	Mexico	CUN	Cancún International Airport
5007	Chile	SCL	Comodoro Arturo Merino Benítez International Airport
5008	South America (other)	GRU	São Paulo/Guarulhos–Governador André Franco Montoro International Airport
5009	Australia and New Zealand	SYD	Sydney Kingsford Smith International Airport
5010	South Pacific	NAN*	Nadi International Airport*
5011	Africa West	LOS	Murtala Muhammed International Airport
5012	Africa East	ADD	Addis Ababa Bole International Airport
5013	Africa South	JNB	O. R. Tambo International Airport
5014	China (including Hong Kong)	HKG	Hong Kong International Airport
5015	Japan and South Korea	HND	Haneda Airport
5016	Far East (other)	SIN	Singapore Changi Airport
5017	Indian Sub-continent	DEL	Indira Gandhi International Airport
5018	Asia (other)	BOM	Chhatrapati Shivaji Maharaj International Airport
5019	Middle East	DXB	Dubai International Airport
5020	Israel	TLV	Ben Gurion International Airport
5021	Russia and non-EU former Soviet	SVO**	Sheremetyevo International Airport**
5022	Ireland	DUB	Dublin Airport
5023	Channel Islands	JER	Jersey Airport
5024	France	CDG	Charles de Gaulle Airport
5025	Belgium and Luxembourg	BRU	Brussels Airport
5026	Netherlands	AMS	Amsterdam Schiphol Airport
5027	Germany	FRA	Frankfurt Airport
5028	Scandinavia (EU)	CPH	Copenhagen Airport
5029	Baltic States	RIX	Riga International Airport
5030	Poland	KRK	John Paul II International Airport Kraków-Balice
5031	Central Europe (EU)	VIE	Vienna International Airport
5032	Bulgaria and Romania	OTP	Henri Coandă International Airport
5033	Iberian Peninsula	ALC	Alicante-Elche Airport

DfT Code	Region	IATA Code	Airport Name
5034	Canary Islands	TFS	Tenerife South Airport
5035	Italy	FCO	Leonardo da Vinci International Airport
5036	Greece and EU Eastern Mediterranean	ATH	Eleftherios Venizelos International Airport
5037	Iceland (and Greenland)	KEF	Keflavík International Airport
5038	Norway	OSL	Oslo Gardermoen Airport
5039	Switzerland and Liechtenstein	ZRH	Zurich Airport
5040	Non-EU Balkan	TIA	Tirana International Airport
5041	Turkey	IST	Istanbul Airport
5042	African Mediterranean	RAK	Marrakesh Menara Airport
5043	Dublin	DUB	Dublin Airport
5044	Brussels	BRU	Brussels Airport
5045	Berlin	BER	Berlin Brandenburg Airport
5046	Dusseldorf	DUS	Düsseldorf Airport
5047	Hamburg	HAM	Hamburg Airport
5048	Munich	MUC	Munich Airport
5049	Copenhagen	CPH	Copenhagen Airport
5050	Stockholm	ARN	Stockholm Arlanda Airport
5051	Budapest	BUD	Budapest Ferenc Liszt International Airport
5052	Vienna	VIE	Vienna International Airport
5053	Alicante	ALC	Alicante–Elche Airport
5054	Barcelona	BCN	Barcelona El Prat Airport
5055	Madrid	MAD	Madrid-Barajas Adolfo Suárez Airport
5056	Malaga	AGP	Málaga–Costa del Sol Airport
5057	Lisbon	LIS	Lisbon Portela Airport
5058	Milan	MXP	Milan Malpensa Airport
5059	Rome	FCO	Leonardo da Vinci International Airport
5060	Athens	ATH	Eleftherios Venizelos International Airport
5061	Oslo	OSL	Oslo Gardermoen Airport
5062	Geneva	GVA	Geneva International Airport
5063	Zurich	ZRH	Zurich Airport
5064	Paris CDG	CDG	Charles de Gaulle Airport
5065	Amsterdam	AMS	Amsterdam Schiphol Airport
5066	Frankfurt	FRA	Frankfurt Airport
5067	Dubai	DXB	Dubai International Airport

Note:
* South Pacific was not present as a region in the CAA dataset. Nadi International Airport in Fiji was thus chosen as a representative airport.
** Given the current ongoing geopolitical conflict, there are no flights from the UK to Russia. Shereme- tyevo International Airport was chosen as the representative airport based on pre-conflict air traffic movements.

References

[1] *UK airport data November 2024 | Civil Aviation Authority*. URL: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/uk-airport-data-2024/november-2024/ (visited on 02/01/2025).

5.2 Scenario Construction

The following chapter outlines the methodology used to construct four distinct scenarios for assessing the operational efficiency improvements in the aviation sector. Each scenario is constructed by specifying the **efficacy**, i.e. the percentage of the potential improvement realized, and the **rollout**, i.e. the percentage of flights implementing this measure, for each measure in each year.

The construction of these scenarios involves a degree of subjectivity. While modeling and literature have been used to inform the assumed values where possible, exact predictions of future adoption and efficacy remain uncertain. Where available, findings from industry reports, academic studies and expert opinions have been incorporated, however, in cases where such evidence was unavailable, assumptions have been made on the basis of expert judgement.

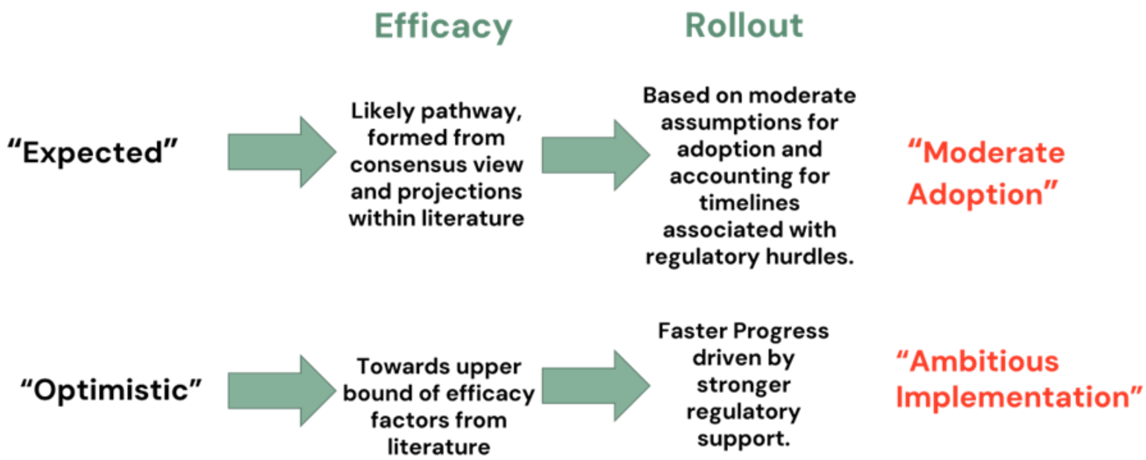
5.2.1 Scenario Definitions

Each of the four scenarios represents a different trajectory for the adoption and effectiveness of operational efficiency measures. The scenarios vary based on assumptions around technical progress, policy support and industry engagement.

In the pessimistic scenario, improvements are minimal or non-existent due to regulatory, financial or technological barriers. The expected scenario reflects a likely pathway given current policy and industry trends. It represents a consensus view of the projections and efficacies shown within the existing literature. The optimistic scenario assumes faster and higher adoption rates for measures as well as rapid technological progress driven by stronger regulatory support. The technical limit represents the absolute maximum fuel savings possible without consideration of the aforementioned hurdles with full optimization of all the technological and operational factors.

Note: Presented below are detailed tables outlining the values assigned to each measure within each scenario. The tables use different descriptors in the subheadings for various scenarios (e.g., 'conservative progress' for the pessimistic case) to emphasize the underlying assumptions regarding efficacy and rollout. While the rest of the document primarily refers to scenarios as pessimistic, expected, and optimistic, the tables use alternative labels such as 'conservative progress,' 'moderate adoption,' and 'ambitious im- plementation' to provide a more intuitive framing of potential outcomes.

Figure 5: Ambition Scenario Examples



Scenario 1: Conservative Progress

Measure	Measure Category	Efficacy	Rollout	Notes
Horizontal Deviation	Air Traffic Management	0.0% for all years	2025: 0%, 2060: 0%, Linear	
Vertical Deviation	Air Traffic Management	0.0% for all years	2025: 0%, 2060: 0%, Linear	
Speed Deviation	Air Traffic Management	0.0% for all years	2025: 0%, 2060: 0%, Linear	
Continuous Climb Operations	Air Traffic Management	98.0% for all years	2025: 0%, 2060: 0%, Linear	
Continuous Descent Operations	Air Traffic Management	60.3% for all years	2025: 0%, 2060: 0%, Linear	
APU Shutdown	Auxiliary Power Unit	90% for all years	2025: 0%, 2050: 100%, Linear	
Formation Flying	Drag Reduction	1.802% (short), 4.182% (medium), 5.236% (long) for all years	0% in all years	
Taxi Choice	Taxiing	20% (out) & 3% (in) for all years	2025: 0%, 2045: 50%, Linear	Single Engine Taxi
Lightweight Cabin	Mass Reduction	0.6% max (range dependent) for all years	2025: 0%, 2040: 100%, Linear	

Scenario 2: Moderate Adoption

Measure	Measure Category	Efficacy	Rollout	Notes
Horizontal Deviation	Air Traffic Manage-ment	1.4% for all years	2030: 0%, 2060: 50%, Linear	
Vertical Deviation	Air Traffic Manage-ment	1.04% for all years	2030: 0%, 2060: 50%, Linear	
Speed Deviation	Air Traffic Manage-ment	0.93% for all years	2030: 0%, 2060: 50%, Linear	
Continuous Climb Operations	Air Traffic Manage-ment	98.0% for all years	2030: 0%, 2060: 50%, Linear	
Continuous Descent Operations	Air Traffic Manage-ment	60.3% for all years	2030: 0%, 2060: 50%, Linear	
APU Shutdown	Auxiliary Power Unit	92.5% for all years	2025: 0%, 2040: 100%, Linear	
Formation Flying	Drag Re-duction	2.20% (short), 5.10% (medium), 6.391% (long) for all years	2040: 0%, 2060: 0%, Linear	
Taxi Choice	Taxiing	Tug: 95% for all years, Single-Engine: 30% (out) & 10% (in) for all years	Tug: 2025: 0%, 2040: 50%, Linear, Single-Engine: 2025: 0%, 2040: 25%, Linear	Electric Tug & Single-Engine Taxi

Measure	Measure Category	Efficacy	Rollout	Notes
Lightweight Cabin	Mass Reduction	0.6% max (range dependent) for all years	2025: 0%, 2035: 100%, Linear	

Scenario 3: Ambitious Implementation

Measure	Measure Category	Efficacy	Rollout	Notes
Horizontal Deviation	Air Traffic Management	2.8% for all years	2030: 0%, 2050: 70%, Linear	
Vertical Deviation	Air Traffic Management	1.75% for all years	2030: 0%, 2050: 70%, Linear	
Speed Deviation	Air Traffic Management	1.96% for all years	2030: 0%, 2050: 70%, Linear	
Continuous Climb Operations	Air Traffic Management	98.0% for all years	2030: 0%, 2050: 70%, Linear	
Continuous Descent Operations	Air Traffic Management	60.3% for all years	2030: 0%, 2050: 70%, Linear	
APU Shutdown	Auxiliary Power Unit	95% for all years	2025: 0%, 2030: 100%, Linear	
Formation Flying	Drag Reduction	2.65% (short), 6.15% (medium), 13.1% (long) for all years	2035: 0%, 2070: 30%, Linear	
Taxi Choice	Taxiing	100% for all years	2025: 0%, 2035: 100%, Linear	Electric Tug
Lightweight Cabin	Mass Reduction	0.6% max (range dependent) for all years	2025: 0%, 2030: 100%, Linear	

Scenario 4: Technical Limit

Measure	Measure Category	Efficacy	Rollout	Notes
Horizontal Deviation	Air Traffic Management	2.8% for all years	2025: 100%	
Vertical Deviation	Air Traffic Management	1.75% for all years	2025: 100%	
Speed Deviation	Air Traffic Management	1.96% for all years	2025: 100%	
Continuous Climb Operations	Air Traffic Management	98.0% for all years	2025: 100%	
Continuous Descent Operations	Air Traffic Management	60.3% for all years	2025: 100%	
APU Shutdown	Auxiliary Power Unit	95% for all years	2025: 100%	
Formation Flying	Drag Reduction	2.65% (short), 6.15% (medium), 13.1% (long) for all years	2025: 50%	
Taxi Choice	Taxiing	100% for all years	2025: 100%	Electric Tug
Lightweight Cabin	Mass Reduction	0.6% max (range dependent) for all years	2025: 100%	

Note: The efficacy percentages refer to the potential for improvement in terms of fuel savings. Taking the particular example of horizontal deviation in the technical limit scenario where there is a 2.8% horizontal inefficiency, there is thus a potential of improvement by up to 2.8% as a result of greater route adherence.

5.2.2 Caveats

Warning: For some operational measures, their rollout has already begun. For this analysis, a datum in 2025 is taken, where each measure begins with a rollout factor of 0. Therefore, the rollout factor displayed represents the rollout into the *remaining* flights.

Note: The efficacy factors are based on literature, and thus the scenarios are informed and bounded by the values within studies. APU shutdown can be pinpointed as one particular example where 100% efficacy was not assigned to the technical limit, given that the highest efficacy within literature was 95%, which reflects the practical reality that perfect efficiency can sometimes be difficult to achieve given operational and technological constraints. In the case of APU shutdown, APUs are considered critical backup systems for electrical power and air conditioning on ground, so some fuel may still need to be carried on board for that reason, meaning savings cannot be 100%. The chosen efficacy factors reflect a balance of improved operational efficiency and likely the need to consider system reliability and flexibility in unexpected cases.

Note: For each measure, it is sensible to assume that the rollout plateaus after reaching the highest value stated in the table above. This is because it has either reached 100%, or some other percentage represents the highest sensible rollout likely to be achieved.

6 Great Circle Uplift Factors

6.1 Great Circle Distance Uplift Factors

Warning

This documentation refers to uplift factors. The DfT refer to uplifts as dimensionless factors which allow determination of the real flight distance through the great circle distance.

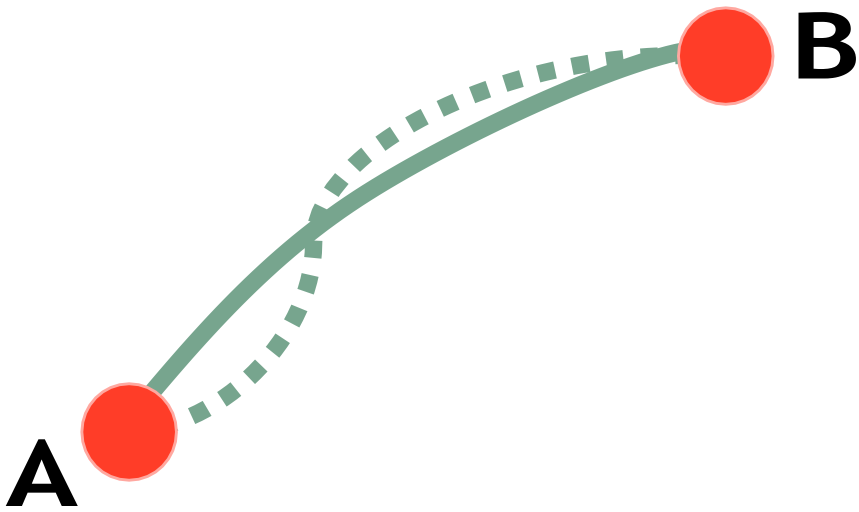
The AIA, however, uses an alternative definition of uplifts where:

$uplift = value_{new} - value_{original}$

Therefore, in this documentation, we refer to uplift factors, which is the more intuitive lexical choice for a dimensionless constant factor. The definition of uplift factor, f_uplift, is thus:

$\int uplift$ = Real Flight Distance / Great Circle Distance

The great circle distance (GCD) refers to the shortest distance between two points on the surface of a sphere. However, aircraft tend to deviate from this shortest path distance due to various technical, natural, geopolitical, and social factors. It is important to be able to account for this within modelling since these deviations lead to a higher real flight distance and thus increased fuel consumption.



From the image above, the curved solid line represents the GCD from A to B and the dotted line represents the actual flight path which may deviate from the GCD.

6.1.1 Review of GCD Uplifts from Literature

There is a range of literature which aim to estimate the deviation of the real flight path from the GCD.

The magnitude of detours faced by commercial flights: A global assessment

In the study conducted by Dobruszkes and Peeters, it was found that short-haul flights proportionally incur longer detours [2]. The detour factor is collated below by route type.

	Average	Short Haul	Medium Haul	Long haul
Detour Factor (+%)	7.6	14.3	7.3	4.8

Assumption:
This work analyzed one week of historical flight data from Flightradar. The time frame for the data is between 3-9 November, 2017. The analysis was thus conducted with a sample of 393,360 flights.

Flight distance modelling to evaluate flight efficiency and environmental impact

For short and medium-haul routes, De Alaminos created a model in order to be able to find the real flight distance as a function of the GCD [3]. Using a least squares approach, focusing only on European airspace, the following function was obtained:

$$\text{Flight Distance [km]} = 1.047x_{GCD} + 78.31 \tag{3}$$

Assumption: This model is only valid up to GCDs of 2500km.

Assuming a rough range of 350km (approximately the distance from London to Paris) to 1500km, the GCD detour factor is thus calculated to be in the range of 9-27% for short-haul flights. Similarly, for medium haul flights between 1500km and 2500km, the detour factor is computed to be 7.8-9%.

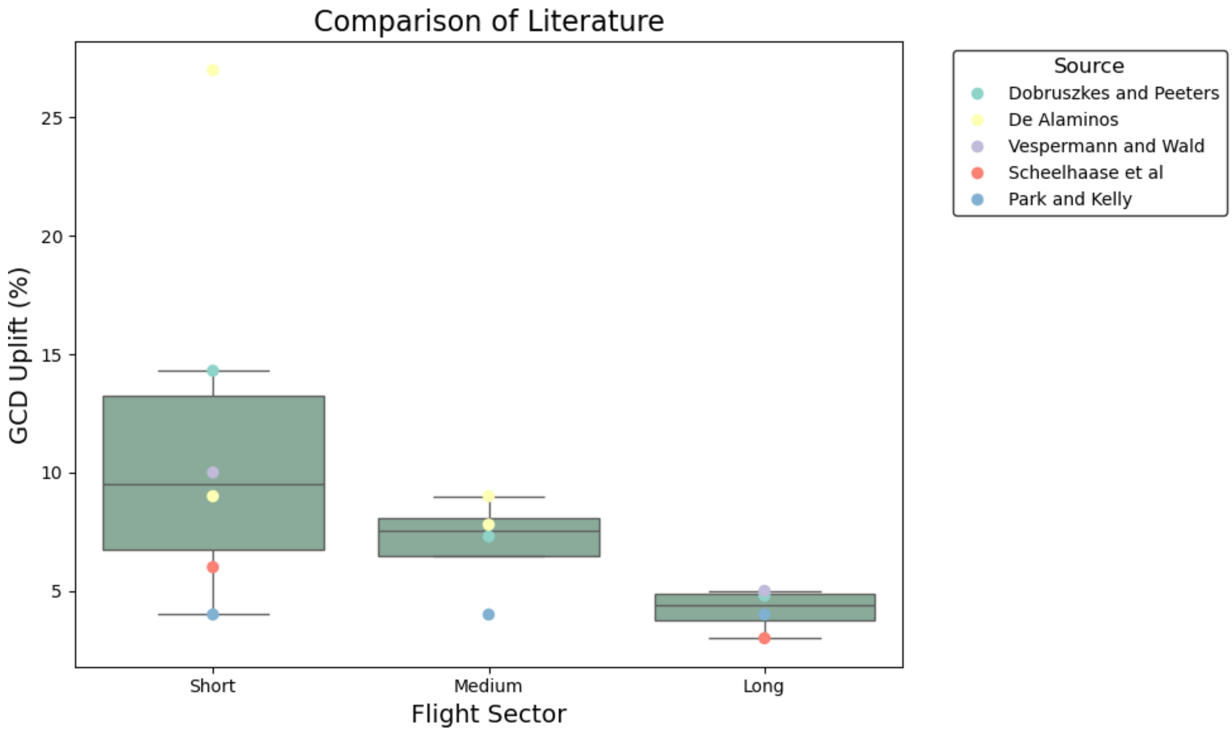
Other Literature

In this section, the GCD uplift factors used by different authors in their bodies of work relative to aviation efficiencies are discussed. For some of these works, an explicit justification has not been given for the use of certain GCD uplifts, but rather is a key assumption made in the study.

Vespermann and Wald assume increases 5% and 10% for long and short haul sectors, respectively [4]. On the other hand, Scheelhaase et al assume uplift factors of 3% and 6%, respectively [5]. Finally, Park and Kelly applied a common uplift factor of 4% to all flights [6].

Figure 6: Comparison of Literature

The plot below shows the spread of literature estimates for GCD uplift by flight sector.



This analysis highlights how there is relative agreement on the rough GCD uplifts which are used for the long-haul sector of flight operations, but there is a huge range of potential uplifts which can be applied to the short-haul sector. This is to be expected since deviations due to air traffic congestion near airports will account for a larger proportion of the flight when it is short-haul rather than when it is long-haul.

From this analysis, the following is found:

Flight Sector	Lower Quartile	Median	Upper Quartile
Short Haul Detour (+%)	6.75	9.50	13.23
Medium Haul Detour (+%)	6.48	7.55	8.10
Long Haul Detour (+%)	3.75	4.40	4.85

These can thus effectively provide a basis for optimism levels for GCD uplift by flight sector.

Note: It should be noted that the optimistic, expected, and pessimistic scenarios are derived from the data presented above rather than relying on assumptions, reflecting a data-driven approach to finding variability in flight inefficiencies and thus their impact on detour factors.

6.1.2 Evolution of GCD Uplifts

GCD uplifts additionally have a temporal aspect, which is governed by various technological and operational improvements in the future. These can be through advancements in navigation technology and dynamic routing which could be used to optimize for GCD routes. Alternatively, there could be improvements in air-traffic management, reducing airspace congestion.

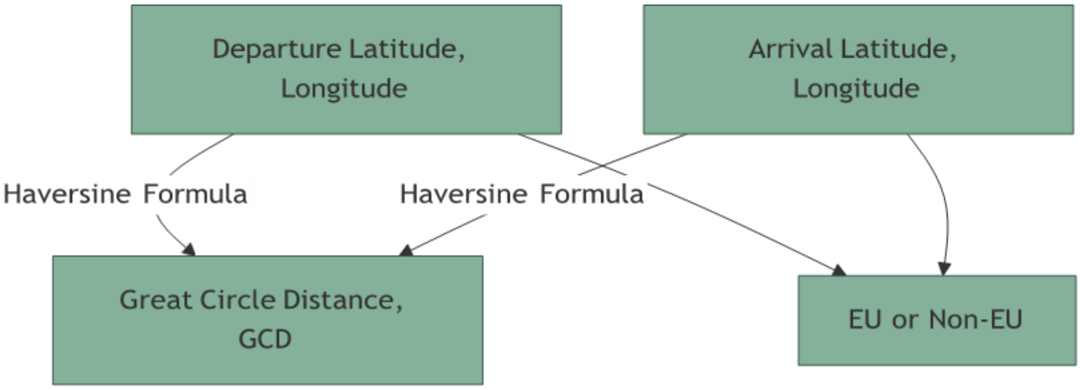
A model to compute improvements in GCD uplifts is thus needed in order to account for modernization of airspace management systems.

6.1.3 Model Overview

The model combines insights from the literature review conducted in the preceding sections in order to assign a GCD uplift.

The following diagrams illustrate the conditional logic within this model for the base GCD uplift factor (without applying factors for future evolution). The departure and arrival airport coordinates are first required in order to compute the GCD. The model varies depending on whether both departure and arrival airports are within European airspace, which is also found through the coordinates. This is shown:

Figure 7: Calculating GCD uplift factor



The logic for handling EU vs non-EU airspace is shown below:

Figure 8: Within European Airspace

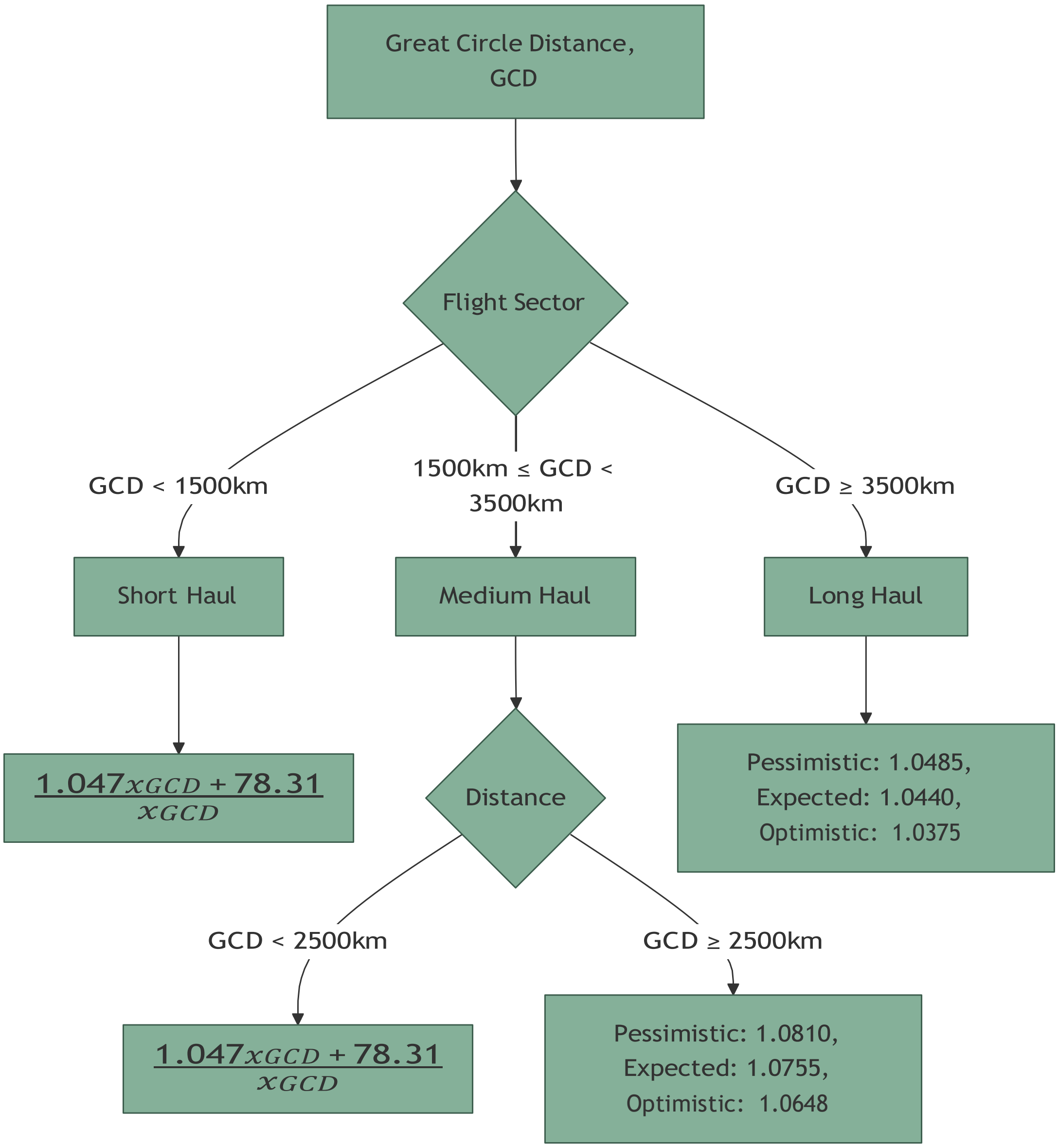
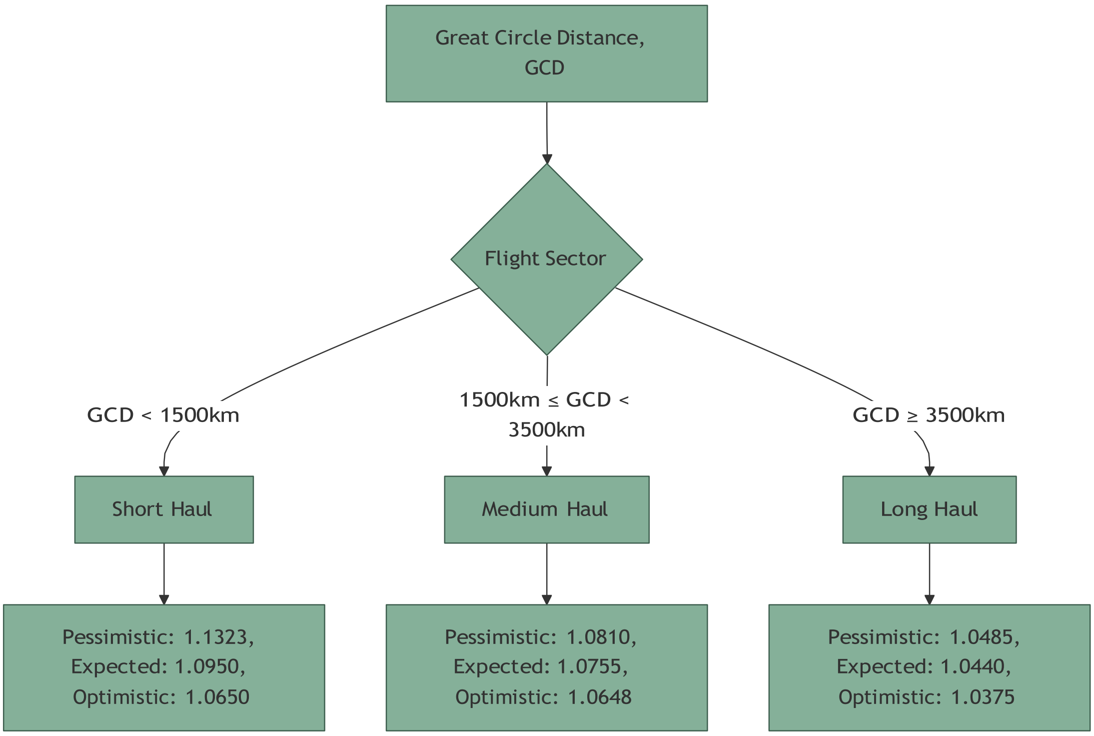


Figure 9: Not within European airspace



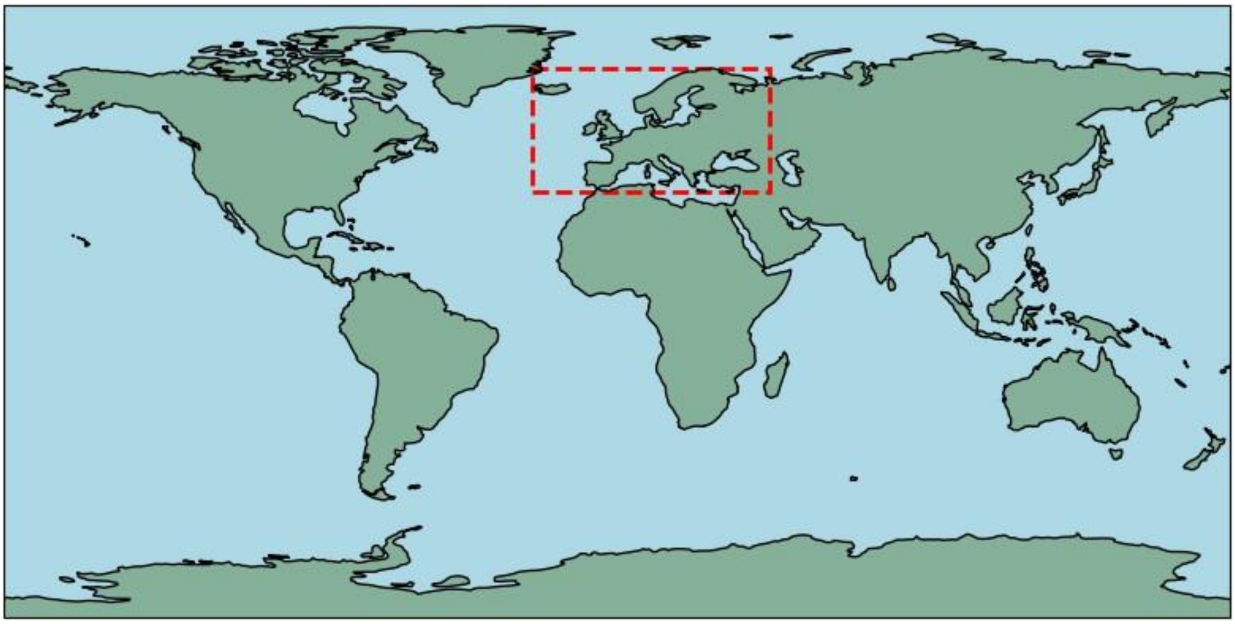
Note:

Whilst the diagrams illustrate optimisms for GCD uplift factors by flight length, it should be noted that a technical limit has not been defined. The notion of a technical limit for GCD uplift is misguided for several reasons. The first is that it assumes that a theoretical perfect route with zero uplift is possible; however in reality, flights are constrained by airspace structures and adverse weather conditions, making a perfect GCD route unrealistic. Secondly, even if a perfect GCD route were made possible, it assumes that flying the GCD is always desirable, when in fact the optimal flight path is dependent on wind conditions etc., rather than just being based on the shortest path. Thus, a technical limit is not provided in order to avoid potential misconceptions.

In this model, the GCD is used in order to classify a flight into the appropriate sector of flight operations. The model uses distance classifications, as specified by the Civil Aviation Authority (CAA) [7]. An airport is classified as being in Europe or outside of Europe through the use of the following bounds on longitude and latitude. Due to the low-order nature of the modeling elsewhere, this approximation of bounds is valid. While it may classify some airports outside Europe as being within its boundaries, the effect of these misclassifications is minimal. This is because the broader context of the model tolerates such simplifications without significantly affecting overall accuracy or insights.

	Maximum	Minimum
Latitude (°)	71.0	35.0
Longitude (°)	45.0	-25.0

These bounds are illustrated below:



Note: Note that the latitude and longitude bounds cover some North African destinations which the DfT consider as being European.

6.1.4 Summary

GCD uplift factors indicate the additional distance flown beyond the great circle distance (GCD), due to operational constraints, including technical factors (such as route design, air traffic congestion, time to alternate airports), natural factors (such as avoidance of weather events, natural local relief) and geopolitical reasons (such as no-fly zones and conflict zones). GCD uplift factors vary by flight length and by geographical region. Generally, it is found that shorter flights incur greater GCD uplift factors given that a fixed amount of deviation can account for a larger proportion of the overall flight distance. This is in contrast with longer-haul flights, which have longer cruise phases, meaning deviations become less significant in light of the overall flight path.

6.1.5 Nomenclature

Variable Names

Symbol	Definition	Unit
x	Flight Distance	km

References

[2] Frédéric Dobruszkes and Didier Peeters. “The magnitude of detours faced by commercial flights: A global assessment”. In: *Journal of Transport Geography* 79 (July 2019), p. 102465. ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2019.102465. URL: https://www.sciencedirect.com/science/article/pii/S0966692318305544 (visited on 01/10/2025).

[3] Alvaro Gascón De Alaminos. “Flight distance modelling to evaluate flight efficiency and environmental impact”. eng. Accepted: 2022-07-26T09:22:21Z. Bachelor thesis. Universitat Politècnica de Catalunya, July 2022. URL: https://upcommons.upc.edu/handle/2117/371090 (visited on 01/13/2025).

[4] Jan Vespermann and Andreas Wald. “Much Ado about Nothing? – An analysis of economic impacts and ecologic effects of the EU-emission trading scheme in the aviation industry”. In: *Transportation Research Part A: Policy and Practice*. A Collection of Papers:Transportation in a World of Climate Change 45.10 (Dec. 2011), pp. 1066–1076. ISSN: 0965-8564. DOI: 10.1016/j.tra.2010.03.005. URL: https://www.sciencedirect.com/science/article/pii/S0965856410000443 (visited on 01/13/2025).

[5] Janina Scheelhaase, Wolfgang Grimme, and Martin Schaefer. “The inclusion of aviation into the EU emission trading scheme – Impacts on competition between European and non-European network airlines”. In: *Transportation Research Part D: Transport and Environment*. Air Transport, Global Warming and the Environment 15.1 (Jan. 2010), pp. 14–25. ISSN: 1361-9209. DOI: 10.1016/j.trd.2009.07.003. URL: https://www.sciencedirect.com/science/article/pii/S1361920909000844 (visited on 01/15/2025).

[6] Yongha Park and Morton E. O’Kelly. “Fuel burn rates of commercial passenger aircraft: variations by seat configuration and stage distance”. In: *Journal of Transport Geography* 41 (Dec. 2014), pp. 137–147. ISSN: 0966-6923. DOI: 10.1016/j.jtrangeo.2014.08.017. URL: https://www.sciencedirect.com/science/article/pii/S0966692314001793 (visited on 01/15/2025).

[7] CAA. *Cancellations | Civil Aviation Authority*. 2025. URL: https://www.caa.co.uk/passengers-and-public/resolving-travel-problems/delays-and-cancellations/cancellations/ (visited on 01/16/2025).

7 Operational Measures Methodology

7.1 Empirical Fuel Burn Methodology

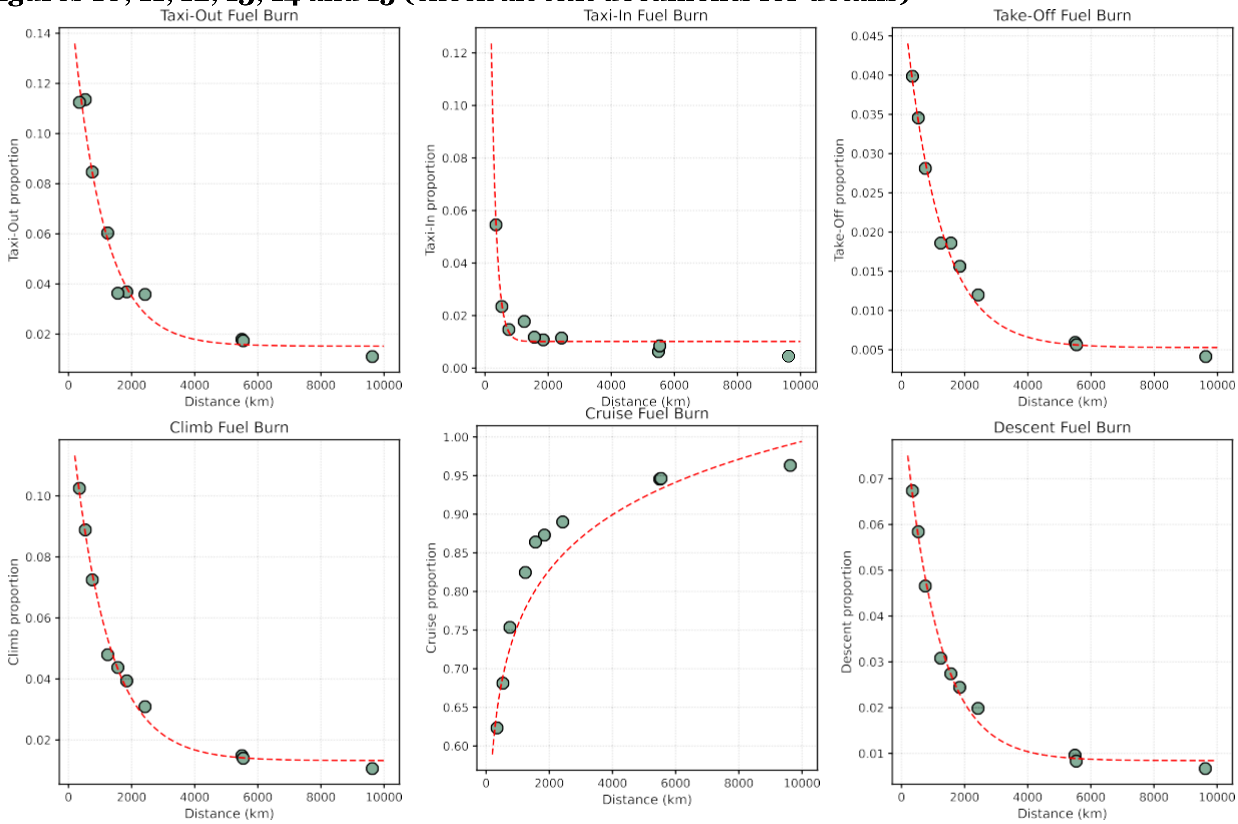
The efficiency measures reduce fuel burn during one or more phases of flight. The AIA's model attributes the fuel burn reduction to each phase depending on the active measures, and then sums the fuel burn within the phases to calculate the total compared to the baseline case. As the analysis conducted within this sprint is based on empirical evidence, not a first-principles, physics-based flight model, an estimate of the relative magnitude of fuel burn within each phase of flight is required.

Note: The AIA utilized an empirical model in order to compute fuel burn, where the relationship between route GCD and fuel burn by phase of flight is derived from existing aircraft fleet and their respective flight fuel burn data. This simplifies the analysis, suitable for the low-order analysis in subsequent parts of the operational efficiency model. In contrast, a physics-based model would require detailed inputs for aircraft engine and aerodynamic variables. This can require increasingly granular data and a detailed understanding of not just the UK aircraft fleet but global fleet too where the data is not always available, leading to more assumptions. In any case, the higher levels of fidelity required by a physics-based model were deemed unnecessary, given that empirical models are less resource-intensive and thus suitable for applications where large datasets are required to be generated.

OAG modelled 10 flights departing from London Heathrow Airport (LHR) to a range of destinations [8]. These flights were of varying lengths, encompassing the short, medium and long-haul sectors. Flight fuel burn was divided into 6 flight stages, namely: taxi-out, take-off, climb, cruise, approach and taxi-in.

Fits can be applied to this data in order to estimate the proportion of the total flight fuel burn that can be attributed to specific phases of flight. The graph below shows the fits for the various phases.

Figures 10, 11, 12, 13, 14 and 15 (check alt text documents for details)



7.1.1 Empirical Fits for Flight Phases

Phase of Flight	Empirical Fit
Taxi-Out	$P_{taxi-out} = 0.1475e^{-0.001x_{GCD}} + 0.0152$
Take-off	$P_{take-off} = 0.0463042e^{-0.000924888x_{GCD}} + 0.00527152$
Climb	$P_{climb} = 0.119295e^{-0.000880948x_{CCD}} + 0.0132253$
Cruise	$P_{cruise} = 0.0396807 + 0.1036456\log(x_{GCD})$
Descent	$P_{descent} = 0.0801804\ e^{-0.000924888x_{GCD}} + 0.00842549$
Taxi-in	$P_{taxi-in} = 0.386538\ e^{-0.00617295x_{GCD}} + 0.0101175$

Note: The proportion of fuel burn attributed to a specific phase can be represented as P_phase. However, given the use of empirical fits, it means that the following occurs:

$P_{total} = P_{taxi\text{-}out} + P_{take\text{-}off} + P_{climb} + P_{cruise} + P_{descent} + P_{taxi\text{-}in} \neq 1.0$ (4)

The sum of the fuel burn proportions do not always add up to unity, as desired. The fix for this is then to divide by the "total" dimensionless factor for fuel burn (by adding the individual fuel burn components together), in order to preserve the relative ratios between the flight phases. In other words, we normalize the fuel burn proportions, as shown below for taxiing:

$P_{taxi\text{-}out,\ normalized} = P_{taxi\text{-}out} / P_{total}$ (5)

This then has the following effect:

$P_{total,\ normalized} = P_{taxi\text{-}out,\ normalized} + P_{take\text{-}off,\ normalized} + P_{climb,\ normalized} + P_{cruise,\ normalized} + P_{descent,\ normalized} + P_{taxi\text{-}in,\ normalized} = 1.0$
(6)

This method is critically important since it allows corrections for empirical discrepancies and ensures that the total fuel burn proportions sum to one, as desired.

7.1.2 Limitations

Unlike a physics-based flight model, the per-phase fuel burn approach cannot simply account for changes in aircraft mass due to fuel burn reduction on other phases of flight. For example, if a measure reduces fuel burn during climb, if the departure fuel is the same as the original flight the aircraft is comparatively heavier in later phases of flight. In turn, this increases fuel burn during these later phases, offsetting the direct fuel burn reduction. Conversely, if the arrival fuel were constant, the aircraft would see additional benefit after the direct reduction because it would be lighter.

The results obtained with the empirical per-phase approach lie between the values a physics-based model would calculate in the constant departure fuel and constant arrival fuel cases and the fitting approach does not have any significant impact on the operational savings which could be expected from a higher fidelity physics-based approach.

The difference between these two cases becomes significant only for very long range flights. For LHR-PER (14,800 km), a physics-based model predicting an 8% fuel burn reduction with the constant departure fuel assumption would predict an approximately 25% greater reduction with the constant arrival fuel assumption (10% fuel burn reduction). The empirical model would predict around a 9% reduction, depending on when in flight the measures take effect.

For shorter, more frequently flown routes, the change is much smaller as fuel is a comparatively much smaller component of the total aircraft mass at take-off. For STN-BCN (1,200 km), the relative difference between physics-based cases would be just 2.5%.

Possibility: This section alludes to how it is possible to achieve greater overall fuel savings through indirect savings in cases where the aircraft carries only the neccessary quantity of fuel for a given journey. In reality, aircraft carry more fuel than is necessary in a practice known as tankering. In a written submission to the Environmental Audit Committee, the Civil Aviation Authority (CAA) advised that they would support approaches to stop tinkering [9].

7.1.3 Nomenclature

Symbol	Definition	Unit
x_{GCD}	Great Circle Distance	km
$P_{taxi-out}$	Proportion of total fuel burn attributed to taxi-out	-
$P_{take-off}$	Proportion of total fuel burn attributed to take-off	-
l_{climb}	Proportion of total fuel burn attributed to climb	-
P_{cruise}	Proportion of total fuel burn attributed to cruise	-
$P_{descent}$	Proportion of total fuel burn attributed to descent	-
$P_{taxi-in}$	Proportion of total fuel burn attributed to taxi-in	-

References

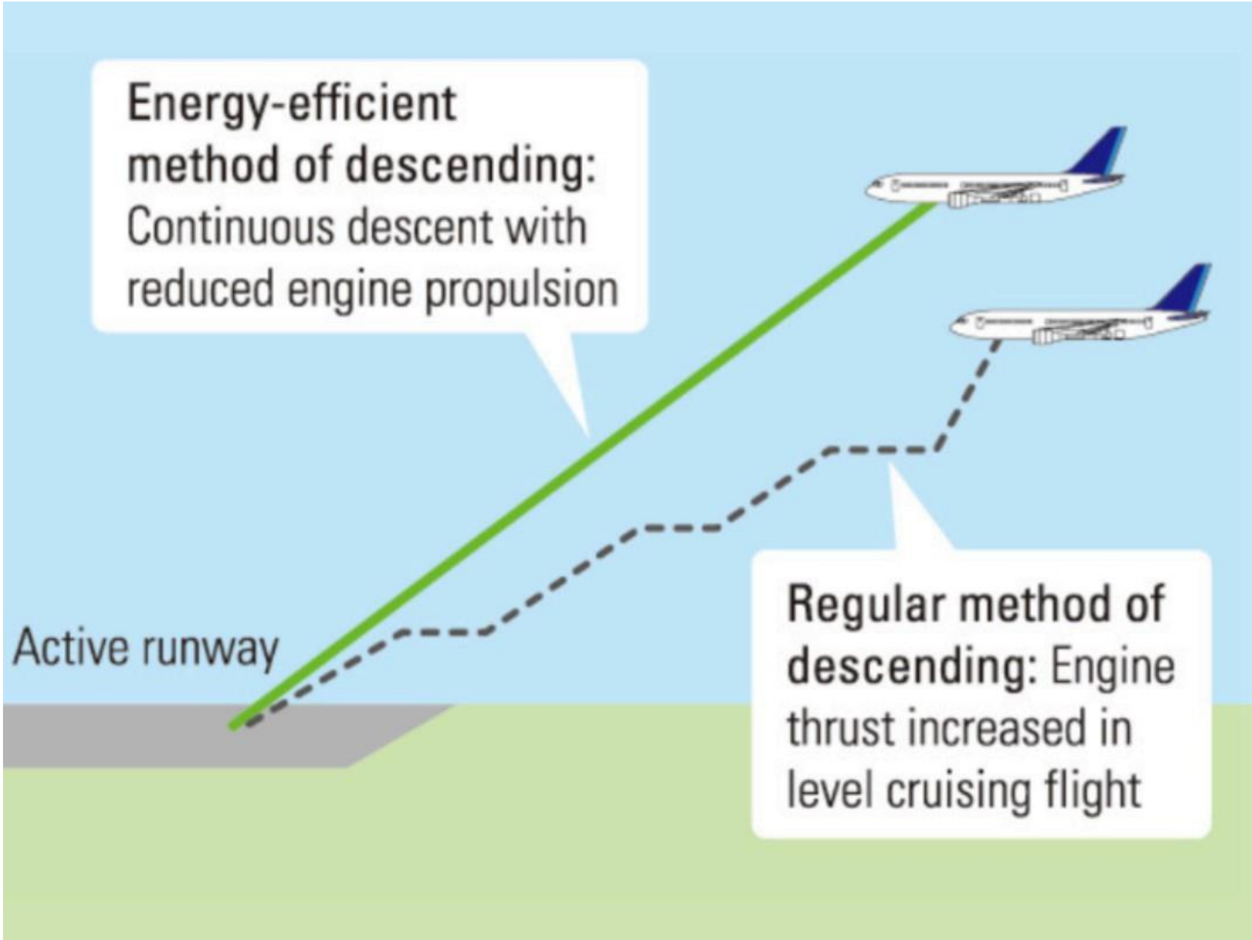
[8] *How Much Fuel Does a Plane Use During Flight? | OAG*. en-gb. URL: https://www.oag.com/blog/which-part-flight-uses-most-fuel (visited on 01/23/2025).

[9] CAA. *Written evidence from the Civil Aviation Authority*. URL: https://committees.parliament.uk/writtenevidence/39348/html/ (visited on 04/09/2025).

7.2 Continuous Climb and Descent Operations

7.2.1 Introduction

In general, aircraft operate most efficiently (lowest fuel burn per distance traveled) at their design cruise conditions. To minimize the total flight fuel burn, an aircraft should ideally ascend to cruise conditions from take-off by climbing, and descend directly from top of cruise to final approach, without interruption. This is known as continuous climb and descent operations (CCO and CDO). The exact climb and descent profiles which minimize flight fuel burn will depend on the aircraft type, its payload and fuel mass, and even current atmospheric conditions.



During a continuous descent, the aircraft spends less time flying at intermediate altitudes[10]

Restrictions such as airport-specific procedures, airspace design limitations and air traffic control may require the aircraft to interrupt its climb/descent and level off, or fly at a non-ideal climb / descent rate or airspeed.

The European CCO/CDO task force was established in 2015 and EUROCONTROL has published a European CCO/CDO Action Plan[10]. Achieving CCO/CDO for all flights may not be practical, due to restrictions on minimum aircraft separation time/distance, weather conditions, and air traffic control capacity and workload.

7.2.2 Model

Data from EUROCONTROL's vertical flight efficiency dataset[11] was used to model the UK potential fuel burn reduction through increased prevalence of CCO/CDO. The dataset reports additional CO_2 emitted due to level flight during descent and climb by airport and month. Time spent in level flight during climb/descent is taken to be a proxy for fuel burn that would be eliminated with CCO/CDO. The total additional mass of CO_2 emitted due to level flight during climb and descent operations into and out of UK airports was first converted to fuel burn, assuming complete combustion of jet fuel.

$$\Delta m_{\text{jet,total}} = \frac{\Delta m_{CO_2,\text{total}}}{EI_{CO_2}} \quad (7)$$

Where complete combustion of jet fuel has a CO_2 emission index of EI_{CO2} = 3.16 [12]. The per-flight average is then calculated using the number of climb and descent operations:

$$\Delta m_{\text{jet,average}} = \frac{\Delta m_{\text{jet,total}}}{N_{\text{operations}}} \tag{8}$$

Flight phase	$\Delta m_{CO_2,\text{total}}$[11]	$\Delta m_{\text{jet,total}}$	$N_{\text{operations}}$[11]	$\Delta m_{\text{jet,average}}$
Climb	15,499 tonnes	4,905 tonnes	1,099,069	4.5 kg/flight
Descent	199,200 tonnes	63,038 tonnes	1,096,068	57.5 kg/flight

Effect of level flight during climb and descent, UK 2024

The EUROCONTROL CO_2 data cannot be directly attributed to flights as a function of distance. The total UK annual additional fuel burn due to level flight is averaged across all flights. This excludes factors which are likely to influence climb and descent fuel burn such as aircraft mass or cruise altitude.

OAG model data is used to estimate absolute fuel burn for different phases of flight, including climb and descent for short, medium and long-haul flights [8], using CAA range definitions[7]. The climb and descent fuel burn is then used to calculate the climb and descent fuel reduction factors, which would be the technical limit with uninterrupted CCO and CDO for all flights.

$$f_{CCO} = \frac{m_{\text{climb}} - \Delta m_{\text{jet,average,climb}}}{m_{\text{climb}}} \tag{9}$$

$$f_{CDO} = \frac{m_{\text{descent}} - \Delta m_{\text{jet,average,descent}}}{m_{\text{descent}}} \tag{10}$$

Flight length classification	Range	m_{climb}	m_{descent}	$f_{CCO,\text{limit}}$	$f_{CDO,\text{limit}}$
Short-haul	s < 1,500 km	227 kg	145 kg	0.980	0.603
Medium-haul	1,500 km < s ≤ 3,500 km	227 kg	145 kg	0.980	0.603
Long-haul	s ≥ 3,500 km	840 kg	526 kg	0.995	0.891

The effect on the phase fuel burn is given by:

$$f = 1 - (1 - f_{\text{limit}})ER \tag{11}$$

Where E is the efficacy factor and R is the proportion of flights adopting the measure.

Note: It may be observed that the AIA's analysis for CCO/CDO operations focus primarily on Europe through the use of EUROCONTROL data, which is more accessible due to centralized data collection and transparency in the reporting of figures. Large scale analyses of this nature are however decidedly hindered in other parts of the world, given limited public access to data as well as variability in airspace management.
However, CCO/CDO operations have been implemented in various regions worldwide. Airservices Australia, for example, initiated a project which is able to optimize the sequencing for air traffic control, allowing predictable continuous descent into airports [13]. This is currently being trialled at Melbourne airport, with an intention to expand the procedures to other Australian airports. ICAO's Asia/Pacific Seamless ATM plan sets out a framework for states to improve flight operations through higher adoption of these measures [14].

7.2.3 Efficacy

It is not possible to predict the rollout and efficacy separately with evidence, for example 50% of flights achieving a 50% reduction in their time spent in level flight during climb/descent versus 25% of flights achieving a 100% reduction. For simplicity, the efficacy is always set as 100% of the technical limit derived above for the two phases so that the rollout controls the measure entirely.

7.2.4 Rollout

In 2024, 22% of descents into UK airports and 63% of climb-outs from UK airports were continuous. The 2024 figures are used as a datum, so that the measure rollout is 0% in 2024.

Note: For this analysis, we consider aircraft that have not yet implemented operational measures such as continuous climb and descent operations, assuming a rollout factor of zero in 2024 as the baseline for adoption. In other words, the 0-100% rollout assumption refers to the 78% of descent operations and 37% of climb operations which are not yet continuous.

Pessimistic

The EUROCONTROL CCO/CDO task force was established in 2015, and the dashboard shows that around 22% of descents were CDO in 2019, as in 2024. CDO reached 41.3% of UK arriving flights in April 2020 due to reduced traffic during COVID-19, but has since returned to around 22% as traffic has returned to pre-pandemic levels. Therefore, it is plausible that no further progress is made on this measure in a pessimistic scenario, due to continued air traffic growth and consequent airspace congestion.

Expected

In this scenario, some progress is made on reducing time spent in level flight during climb and descent, in spite of continued traffic growth. A figure of 50% adoption by 2060 is suggested. This is a reasonable projection, likely to be driven by technological advancements in ATM and regulatory mandates.

Optimistic

Almost all flights achieve CCO/CDO, with the only exceptions being when poor weather conditions, emergencies leading to airspace disruption, or periods of very high air traffic workload / reduced capacity. An adoption of 80% by 2050 is suggested. This requires a rapid acceleration in development of modernized ATM systems in conjunction with early large-scale implementation. Automated dynamic routing, augmented through optimized airspace design, would allow for better traffic flow management, allowing continuous climb/descent operations. This scenario assumes global regulations and strong collaboration between airlines, airports and air navigation service providers (ANSPs).

Technical Limit

100% adoption is achieved.

7.2.5 Nomenclature

Roman Symbols

Symbol	Definition	Unit
E	Efficacy factor	–
R	Rollout (adoption) factor	–
EI	Emissions index	$kgCO_2/kgjet$
f	Fuel burn reduction factor	–
m	Mass	kg

Symbol	Definition	Unit
$N_{operations}$	Number of operations	-
s	Flight great circle distance	km

References

[7] CAA. *Cancellations | Civil Aviation Authority*. 2025. URL: https://www.caa.co.uk/passengers-and-public/resolving-travel-problems/delays-and-cancellations/cancellations/ (visited on 01/16/2025).

[8] *How Much Fuel Does a Plane Use During Flight? | OAG*. en-gb. URL: https://www.oag.com/blog/which-part-flight-uses-most-fuel (visited on 01/23/2025).

[10] *European Continuous Climb and Descent Operations Action Plan | EUROCONTROL*. URL: https://www.eurocontrol.int/publication/european-cco-cdo-action-plan (visited on 02/06/2025).

[11] *Data | Aviation Intelligence Portal*. URL: https://ansperformance.eu/data/ (visited on 02/06/2025).

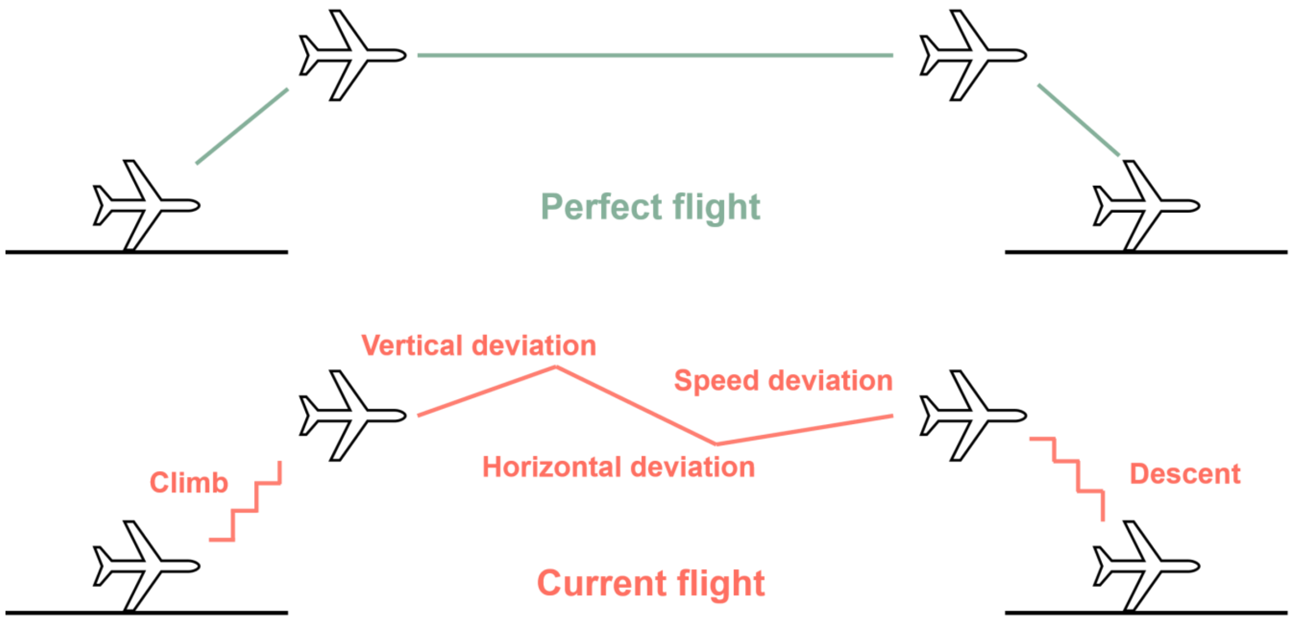
[12] IATA. *IATA Carbon Offset Program FAQs*. Tech. rep. IATA, 2022. URL: https://www.iata.org/contentassets/922ebc4cbcd24c4d9fd55933e7070947/icop_faq_general-for-airline-participants.pdf.

[13] ICAO. *IP07 Continuous Descent Operations (CDO) Trial*. 2023. URL: https://www.icao.int/APAC/Meetings/2023%20ATM%20SG%2011/IP07%20Continuous%20Descent%20Operations%20%28CDO%29%20Trial.pdf (visited on 03/15/2025).

[14] ICAO. *Asia Pacific seamless ans Plan*. 2019. URL: https://www.icao.int/apac/documents/edocs/asia%20pacific%20seamless%20ans%20plan.pdf (visited on 03/15/2025).

7.3 4D Trajectory Management

This chapter discusses the potential fuel savings that can be achieved through 4D trajectory management through optimization of flight path, which is facilitated by ATM improvements and involvement.



Currently, many flights have imperfect trajectories due to factors relating to airspace congestion, adverse weather conditions and inefficient air traffic management. These deviations from the optimal flight path can result in increased fuel consumption. 4D trajectory management in aviation allows optimized flight planning in four dimensions: longitude, latitude, altitude and speed. This allows flights to follow more efficient trajectories for reduced fuel consumption.

This means mitigating against horizontal, vertical and speed deviations in flight.

Horizontal deviation refers to the lateral displacement of an aircraft from its planned flight path (which may not necessarily be the GCD but a wind-optimized route). Reasons for horizontal deviation include: adverse weather avoidance, ATC instructions and avoidance of conflict zones.

Vertical deviation occurs when an aircraft strays from its optimal altitude. Turbulence at a certain altitude may mean that an aircraft is then redirected to an alternative flight level. Congested airspace may mean that flights do not fly at the optimal altitude if other aircraft already occupy the flight level.

Speed deviation happens when an aircraft deviates from the optimal speed with respect to fuel efficiency. Alongside weather and ATC constraints, a key reason why speed deviation can occur is due to airline flight planning through the use of cost indices which aim to balance fuel costs with overall airline operating costs (which correlate with time-related costs).

7.3.1 Review of Efficacy from Literature

Full efficiency benefits and implementation considerations for cruise altitude and speed optimization in the National Airspace system

Jensen[15] utilized a cruise-phase fuel burn estimator in order to examine the potential for flexible vertical navigation (VNAV) optimization for over 200,000 flights. He found that 33% of flights from his sample had optimization benefits ranging from 0-0.5%, indicating that around a third of flights from within the sample were operating at roughly the optimal altitude. The median and mean **cruise** fuel burn reduction found for the dataset was 1.04% and 1.75% respectively. 25% of flights, however, achieved a **cruise** fuel burn reduction greater than 4.61%.

The analysis was repeated for speed optimization. Two variations of speed optimization was conducted: Maximum Range Cruise (MRC) and Long Range Cruise (LRC) speeds. The MRC speed refers to the absolute fuel-optimal speed, whereas LRC is an industry-standard metric which considers the trade-off between time and fuel usage. MRC speed optimization achieved median and mean **cruise** fuel burn reductions of 1.24% and 1.96%, respectively. 25% of flights can have greater than 2.83% fuel burn reduction potential. These figures for LRC speed optimization were 0.39%, 0.93% and 1.82%, respectively.

This analysis includes consideration of wind-optimized routing.

EUROCONTROL

Eurocontrol[11] data suggests that the average enroute horizontal inefficiency is 2.8% within European airspace, which is thus defined as the technical limit.

Warning: The 2.8% value refers to the current horizontal inefficiency within European airspace, i.e. a 2.8% deviation from the optimal intended flight path (not to be confused with the great circle distance which is the shortest distance between two points on a sphere). However, it does not imply that the maximum horizontal deviation across all routes globally is 2.8%. The lack of global data on horizontal deviation can be attributed to the complexities and the variability of airspace management across different world regions. A unified dataset on global horizontal inefficiency is difficult to obtain, while European airspace has standardized procedures and thus readily accessible data.In this analysis, we have assumed that this horizontal inefficiency applies globally given the reasons above. In 2015, the horizontal en-route inefficiency for flights to and from 34 major airports in Europe was 2.83%, compared to the 2.92% estimated within US airspace [16], suggesting broadly similar inefficiency levels. In horizontal inefficiency analysis conducted by ICAO in 2017, it was found that the Middle East and the Asia-Pacific region were outliers, experiencing greater inefficiencies [17]. Thus the 2.8% value will be an underestimate of the inefficiency for those areas.

Note: Reducing horizontal inefficiency through optimized routing can have an impact on GCD uplift, potentially bridging the gap between the great circle distance and the planned route. Whilst the shortest distance (GCD) isn't always the most optimal route (due to wind and airspace restrictions), better air traffic flow management can facilitate certain flight paths to be both operationally more optimal as well as closer to the theoretical shortest route. This means that for certain routes, reducing horizontal inefficiency could indirectly also lower GCD uplift over time.For this analysis, we present an analysis on estimates for GCD uplifts, but it is not included as part of the dataset to avoid double counting with horizontal inefficiency given that the two numbers are not fully independent.

Summary of Efficacy Factors from Literature

Type of Trajectory Optimization	Pessimistic (%)	Expected (%)	Optimistic (%)
Vertical	0.0	1.04	1.75
Speed	0.0	0.93	1.96
Horizontal	0.0	1.4	2.8

The efficacy factors for the expected and pessimistic cases for the vertical and speed deviations are taken directly from literature. For the horizontal trajectory optimization, the AIA assumes an efficacy of 50% relative to the optimistic case, resulting in an efficacy factor of 1.4%. This reflects variability in flight conditions, such as adverse weather or airspace constraints. The 1.4% thus represents a more conservative estimate, accounting for a range of scenarios where trajectory correction may not be possible. The AIA further assumes that technical limitations such as insufficient real-time data which is required for trajectory optimization may result in severely limited capacity to tackle flight path deviations. Thus, the pessimistic scenario assumes 0% efficacy as the worst-case scenario.

7.3.2 Rollout

The implementation of trajectory-based optimization requires additional clearances and coordination, increasing pilot and ATC workloads. It is also dependent on frequent weather forecast updates, with a requirement on increasing accuracy over longer periods of time to allow planning. There is a need for advanced ATM systems to monitor aircraft without fixed waypoints.

The FAA is currently developing systems which allow dynamic trajectory-based optimization for flights, with full implementation expected to occur after 2030[18]. NASA has also developed an aircraft flight automation system, which is able to find weather-optimized routes, however a timeline for wider implementation is not yet clear[19].

Within Europe, EUROCONTROL is leading deployment of trajectory-based operations (TBO) in alignment with ICAO's vision, supported by the Single European Sky ATM Research (SESAR) program. SESAR aims to develop advanced technologies and procedures for real-time flight trajectory sharing. EUROCONTROL's Network 4D Trajectory Concept of Operations is a vision based on the future conceptual evolutions related to TBO[20]. Within the UK, similar steps are being taken through the airspace modernization program initiated through the joint collaboration of the Department for Transport and the UK Civil Aviation Authority[21]. These initiatives lay the groundwork for the rollout of dynamic trajectory optimization.

For ATM-related operational measures, the AIA assumes that in the pessimistic case, any impact of these measures will be offset by the increase in air traffic congestion due to increased air traffic movements and demand for airspace. With the view that advanced automated ATM systems will start to come in 2030, an expected rollout of 50% by 2060 is assumed. This is comparable to scenarios from ICAO[22]. For the optimistic case, the AIA assumes wide implementation of the systems referenced above, with 70% rollout by 2050.

References

[11] *Data | Aviation Intelligence Portal*. URL: https://ansperformance.eu/data/ (visited on 02/06/2025).

[15] Luke L. Jensen. "Full efficiency benefits and implementation considerations for cruise altitude and speed optimization in the National Airspace system". eng. Accepted: 2014-10-08T15:21:38Z. Thesis. Massachusetts Institute of Technology, 2014. URL: https://dspace.mit.edu/handle/1721.1/90669 (visited on 02/18/2025).

[16] Yulin Liu et al. "Causal analysis of flight en route inefficiency". In: *Transportation Research Part B: Methodological* 151 (Sept. 2021), pp. 91–115. ISSN: 0191-2615. DOI: 10.1016/j.trb.2021.07.003. URL: https://www.sciencedirect.com/science/article/pii/S0191261521001351 (visited on 04/03/2025).

[17] David Brain and Nico Voorbach. *ICAO's Global Horizontal Flight Efficiency Analysis*. en. Tech. rep. ICAO, 2017. URL: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg138-144.pdf.

[18] *FAA, Eurocontrol Pursue Initial Trajectory-Based Operations Now, Full Implementation Later*. URL: //interactive.aviationtoday.com/avionicsmagazine/july-august-2022/faa-eurocontrol-pursue-initial-trajectory-based-operations-now-full-implementation-later/ (visited on 02/19/2025).

[19] *Dynamic Weather Routes Tool | T2 Portal*. URL: https://technology.nasa.gov/patent/TOP2-168 (visited on 02/19/2025).

[20] EUROCONTROL. *Europe takes important steps towards Trajectory-Based Operations | EUROCONTROL*. en. Oct. 2024. URL: https://www.eurocontrol.int/article/europe-takes-important-steps-towards-trajectory-based-operations (visited on 03/15/2025).

[21] Department for Transport. *Airspace modernisation*. en. 2024. URL: https://www.gov.uk/government/publications/airspace-modernisation/airspace-modernisation (visited on 03/15/2025).

[22] *LTAG Report*. URL: https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx (visited on 02/19/2025).

7.4 Auxiliary Power Units

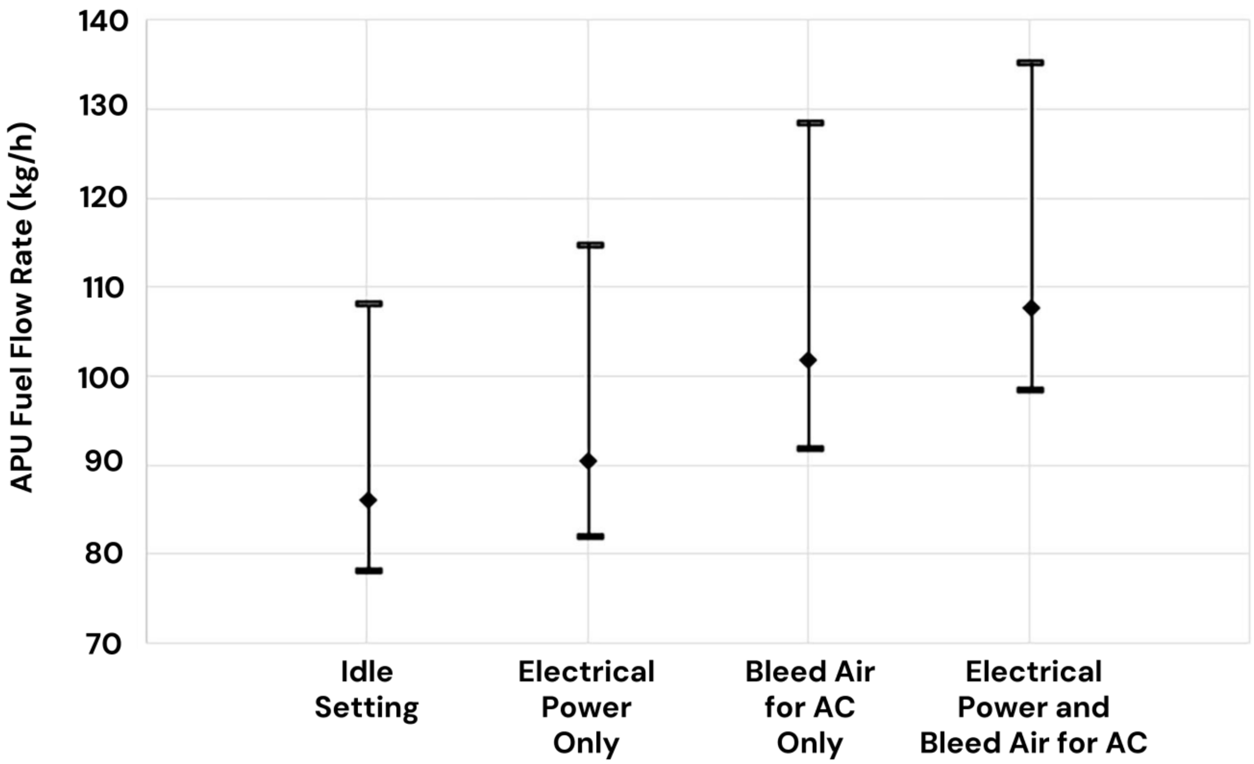
An auxiliary power unit (APU) refers to a small gas turbine which is mounted at the rear of the aircraft's fuselage. Its role is to provide electrical power to onboard systems and supply bleed air to the air conditioning packs during ground operations[23].

According to Heathrow's Emission Inventory from 2017[24], APU emissions can account for around 11-16% of ground-level emissions, which makes it quite a substantial polluting sector of airport operations.

7.4.1 APU Operations

The least energy-intensive mode of APU operation is the idle mode, where the APU is on but not providing electrical power or bleed air. The APU can be operated to provide either one of the two or a combination. The various power settings for APUs are the no-load (NL), environmental control system (ECS) and main engine start (MES) conditions, with different associated fuel flow rates. These fuel indices vary by aircraft category (e.g. narrow-body, wide-body, regional jet, turboprop etc.)[25]. Additionally, these fuel flow rates are also impacted by advancements in APU technology and age, but for a first-order model, these differences in fuel flow have not been considered. Padhra[23] provides a chart with associated fuel consumptions for different modes.

Figure 16: APU Fuel Flow rates for varying modes of operation



APU Fuel Flow rates for varying modes of operation. Taken from Padhra[23].

Thus, mitigations in this sector of operations can come from the following:

- The provision of external electrical power
- The provision of external units for bleed air

7.4.2 Fuel Burn Proportion Estimation

In order to estimate the proportion of taxiing fuel burn which can be attributed to APU usage, we employ the standard LTO cycle as described by ICAO[26], which assumes a thrust setting of 7% for taxiing and a time-in mode of 26 minutes (including both taxi-out and taxi-in) and compare that to a physics-based model for APU fuel consumption.

The selected reference aircraft and their relevant characteristics[26] are shown below:

Aircraft Type	Engine Type	Number of Engines	Taxi Fuel Flow rate (kg/s)
ERJ-145ER	AE3007A1/3	2	0.045
A321neo	CFM International LEAP-1A33B2	2	0.096
A350	Trent XWB-97	2	0.325

The taxi fuel-burn is then computed through the following equation:

$$F_{taxi} = N_{eng}\dot{m}_{taxi}t_{taxi} \tag{12}$$

The APU fuel consumption model assumes hot temperature conditions (to ensure we account for air-conditioning), as described in "Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems"[25]. This model assumes a total APU usage time of 22.18 minutes (comprising of 3.0, 3.6, 0.58 and 15.0 minutes for the APU start (NL), Gate-Out(ECS), Main Engine Start(MES), Gate-In (ECS) phases, respectively).

The fuel indices are shown below:

Aircraft Category	NL Fuel Flow rate (kg/s)	ECS Fuel Flow rate (kg/s)	MES Fuel Flow rate (kg/s)
Regional Jet	0.012	0.019	0.020
Narrow-body	0.021	0.033	0.038
Wide-body	0.035	0.052	0.064

The equation below can thus be used in order to compute APU fuel burn:

$$F_{APU,phase} = \dot{m}_{APU,phase}t_{APU,phase} \tag{13}$$

The various fuel burns are thus shown:

Aircraft Category	Taxi Fuel Burn (kg)	APU Fuel Burn (kg)	Total on-ground Fuel Burn (kg)	Percentage APU Fuel Burn of total on-ground Fuel Burn (%)
Regional Jet	140.4	24.1	164.5	14.7
Narrow-body	299.5	41.9	341.4	12.3
Wide-body	1014.0	66.6	1080.6	6.2

The wide-body percentage is representative for long-haul flights, so for long-haul flights, the percentage of APU fuel burn from taxiing can be fixed at 6%. Whilst regional jets have been modelled, realistically narrow-body aircraft will be used for short and medium-haul flights, so it is sensible to fix the APU fuel burn percentage at 12% for those flight lengths.

7.4.3 Review of APU Mitigations and Efficacies from Literature

Sustainability in ground operations - APU, GPU & PCA

It is suggested from this source[27] that current use of the pre-conditioned air (PCA) units and diesel ground power results in a 50% reduction in emissions, where it is in place. The article speculates that further fuel savings can be achieved through reduction of APU usage times (which can potentially be reduced by 50%).

Thus the range of potential reductions lies between 50% and 75%. This does not account for the use of electric systems, such as fixed electrical ground power (FEGP) systems, thus the actual savings are even higher, as outlined by the other sources.

Development of an Airport System Model for Aviation Impact Accelerator

An internal study of APU usage finds that a best-case scenario which utilizes FEGP at every gate and central PCA systems as well as optimizing the duration of APU usage can result in a 90% reduction in emissions. Shaikh [28] further discusses that an "Airport Collaborative Decision-Making system" could be employed in order to aid with time-related APU operation optimization.

GPUs: The only way is sustainable

Payne [29] suggests that up to 95% reduction can be achieved through the use of electric ground power in conjunction with PCA units. This is roughly in alignment with Shaikh's [28] findings.

7.4.4 Review of Rollout Rates

Frankfurt airport aims to replace all existing diesel ground power units to electric units by 2040[30]. For Frankfurt, which requires 255 ground power connections, has 67% of these already upgraded in 2024. Further 12 positions are expected to be upgraded by 2026, suggesting an upgrade of 6 units a year. Further to this, in order to achieve complete electric power by 2040, which requires upgrading 5 positions a year.

Given Frankfurt's status as an international hub airport, it can be argued that the rollout rate deployed there can effectively be applied to major UK airports due to their comparable size, high passenger traffic and international connectivity. The AIA assumes that for the pessimistic scenario, airports will roll out this measure to 100% by 2050, which is slower progress than what has just been previously discussed. Frankfurt's rollout of electric ground power aligns with UK airports' sustainability goals, serving as a reference for the expected case which also takes into account a broader evaluation of expected APU uptake. The optimistic scenario involves full rollout by 2030. These aggressive measures are based on the fact that this measure is actively being implemented across UK airports today. In fact, Heathrow mandates the use of FEGP and PCA units wherever provided as per its operational safety policies [31]. Additionally, all of Gatwick's stands have FEGP units[32] whilst Bristol[33] and Stansted[34] airports have plans to also increase FEGP usage in order to reduce APU usage.

Note: Despite current widespread use of FEGP systems at airports such as Heathrow and Frankfurt, it is important to also discuss some of the challenges associated with deployment of FEGP systems:

- Planning Permissions - Installation of new infrastructure such as FEGP requires navigating the planning permission processes. Generally speaking, major airport infrastructure develop- ments within the UK are designated as Nationally Significant Infrastructure Projects (NSIPs) [35] under the Planning Act 2008. These processes thus require lengthy assessments and consulta- tions, resulting in longer timelines.
- Electricity Grid connections - There are also often challenges encountered in securing elec- trical connections to the grid, which can again hinder the timeline of deployment [36].
- Operational Flexibility - Airports often use remote stands during busier periods. However, FEGP systems are installed at fixed locations such as at gates. Complete reliance on FEGP systems could then impact airports' abilities to handle high traffic volumes which would require remote stand usage [37].

Information on best practices concerning PCA and FEGP usage at airports can be found in the ACRP Research Report 207.

Whilst comprehensive data on the extent of FEGP rollout is not readily available, FEGP deployment is happening across different airport archetypes, at least within the UK. Heathrow is an intercontinental hub airport with wide-scale usage of FEGP systems and PCA. Gatwick and Bristol represent major and regional airports within the UK, demonstrating that deployment isn't restricted to the biggest airports. It is likely that progress may however be made on different scales with varying timelines, given that smaller regional airports may face resource constraints and may require substantial support.

7.4.5 Nomenclature

Symbol	Definition	Unit
F_{taxi}	Fuel burn attributed to taxiing	kg
$\dot{m}_{taxi}$	Fuel flow rate attributed to taxiing	kg/s
N_{eng}	Number of engines on aircraft	-
t_{taxi}	Time attributed to taxiing operations	s
$F_{APU,phase}$	Fuel burn attributed to an APU phase	kg
$\dot{m}_{APU,phase}$	Fuel flow rate attributed to an APU phase	kg/s
$t_{APU,phase}$	Time attributed to APU usage	s

References

[23] Anil Padhra. “Emissions from auxiliary power units and ground power units during intraday aircraft turnarounds at European airports”. In: *Transportation Research Part D: Transport and Environment* 63 (Aug. 2018), pp. 433–444. ISSN: 1361-9209. DOI: 10.1016/j.trd.2018.06.015. URL: https://www.sciencedirect.com/science/article/pii/S136192091830021X (visited on 02/11/2025).

[24] Charles Walker. *Heathrow Airport 2017 Emission Inventory*. en. 2018. URL: https://www.heathrowairwatch.org.uk/documents/Heathrow_Airport_2017_Emission_Inventory_Issue_1.pdf.

[25] National Academies of Sciences, Engineering, and Medicine. *Handbook for Evaluating Emissions and Costs of APUs and Alternative Systems*. Ed. by Transportation Research Board. 1st ed. Washington, D.C.: Transportation Research Board, May 2012. ISBN: 978-0-309-41041-0. DOI: 10.17226/22797. URL: https://www.nap.edu/catalog/22797 (visited on 02/12/2025).

[26] *ICAO Aircraft Engine Emissions Databank | EASA*. en. URL: https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank (visited on 01/27/2025).

[27] *Insight: Sustainability in ground operations - APU, GPU & PCA*. URL: https://www.assaia.com/resources/apu-emissions (visited on 02/11/2025).

[28] Abdul Rehman Shaikh. *Development of an Airport System Model for Aviation Impact Accelerator*. en. Tech. rep. University of Cambridge, 2020.

[29] Samantha Payne. *GPUs: The only way is sustainable*. en. Section: GSE,Sustainability,UK & Europe,North & South America,Reports. July 2023. URL: https://www.groundhandlinginternational.com/content/features/gpus-the-only-way-is-sustainable/ (visited on 02/11/2025).

[30] Becca Alkema. *Press Release: Frankfurt Airport modernizes ground power supply*. en-US. Feb. 2024. URL: https://runwaygirlnetwork.com/2024/02/press-release-frankfurt-airport-modernizes-ground-power-supply/ (visited on 02/11/2025).

[31] Heathrow. *ASEnv_OSI_078 Use of Aircraft Auxillary Power Units_v2*. 2024. URL: https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/team-heathrow/airside/operational-safety-insttructions/ASEnv_OSI_078%20Use%20of%20Aircraft%20Auxillary%20Power%20Units_v2.pdf (visited on 02/20/2025).

[32] Gatwick Airport. *airspace_GroundNoise*. 2021. URL: https://aircraftnoise.gatwickairport.com/wp-content/uploads/2021/06/airspace_GroundNoise.pdf (visited on 03/05/2025).

[33] Bristol Airport. *2024-2029-nap-awaiting-formal-adoption*. 2023. URL: https://www.bristolairport.co.uk/media/ktddrwq0/2024-2029-nap-awaiting-formal-adoption.pdf (visited on 03/05/2025).

[34] London Stansted Airport. *stn-nap-fixed-electrical-ground-power*. URL: https://assets.live.dxp.maginfrastructure.com/f/73114/x/d848d3ee6a/stn-nap-fixed-electrical-ground-power.pdf (visited on 03/05/2025).

[35] GOV.UK. *Nationally Significant Infrastructure Projects and the people and organisations involved in the process*. en. 2024. URL: https://www.gov.uk/guidance/nationally-significant-infrastructure-projects-and-the-people-and-organisations-involved-in-the-process (visited on 03/15/2025).

[36] Aleksandra Ovchinnikova. *Airport electrification: Solutions for infrastructure challenges*. en. Section: GSE,Airports,Sustainability. 2024. URL: https://www.groundhandlinginternational.com/content/opinion/airport-electrification-solutions-for-infrastructure-challenges/ (visited on 03/15/2025).

[37] Katherine Preston B. et al. *Read "Optimizing the Use of Electric Preconditioned Air (PCA) and Ground Power Systems for Airports" at NAP.edu*. en. ACRP, 2019. DOI: 10.17226/25623. URL: https://nap.nationalacademies.org/read/25623/chapter/8 (visited on 03/15/2025).

7.5 Formation Flight

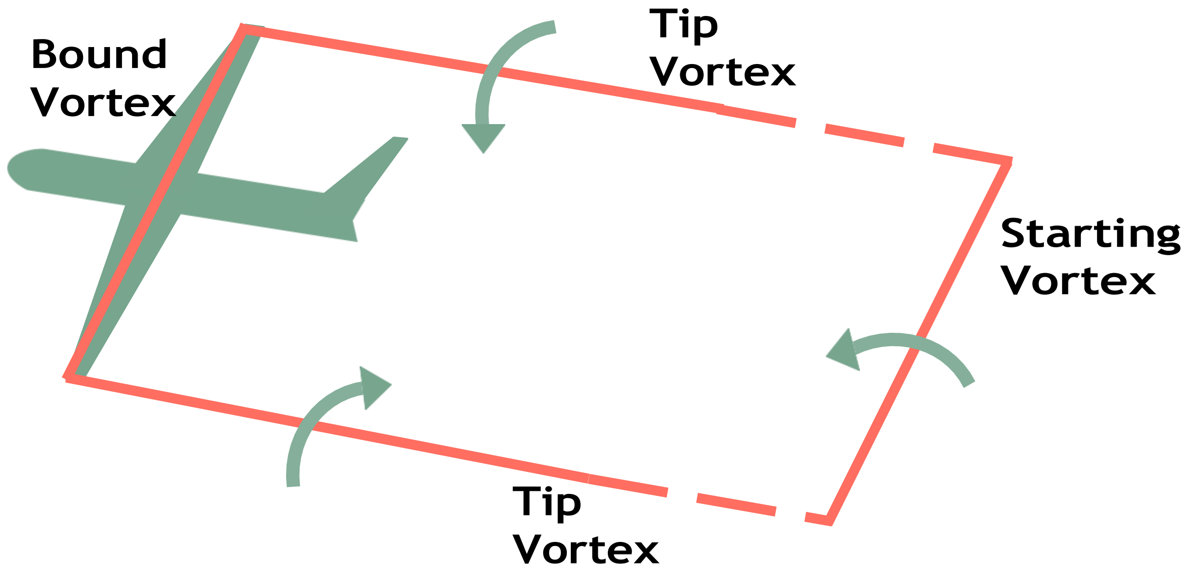
Formation flight involves flying aircraft in coordinated patterns as a drag reduction mechanism.

7.5.1 Description of the drag-reduction mechanism

A prominent feature observed in the flowfield around lift-producing wings is a pair of vortices near the wingtips.

Credit: NASA Langley Research Center

A simple model of this flowfield shows that trailing the aircraft, there is a region of significant downwash inboard of the wingtips, and conversely a region of upwash outboard of the wingtips[38]. This model of the flowfield is known as the horseshoe vortex model.



For a given lift requirement, if a follower aircraft positions itself in the upwash of the flowfield from a leading aircraft, it can reduce its induced drag, the component of drag that arises when lift is produced[39]. This reduction in drag subsequently reduces aircraft fuel burn.

7.5.2 Limitations of Formation Flight

There are several challenges to achieving routine formation flight.

1. Flying in proximity to other aircraft presents a greatly increased collision risk compared to standard separation. Air traffic, procedural and technology mitigations will be needed to achieve regular, safe formation flight.
2. To enable co-operative formation flying between different operators, an agreed system or standard to account for the fuel burn saving and credit the lead aircraft may be required.
3. Multiple flights departing from the same airport around the same time and heading in the same direction must be scheduled.
4. These flights must be able to perform rendezvous in the air without significant delay or holding time.

7.5.3 Review of Formation Flight from Literature

Aircraft Route Optimization for Formation Flight

Xu et al.[39] examined the impact of two/three-aircraft formation flight. Analyzing 20 missions (consisting of 11 solo flights, 7 two-aircraft formations and 2 three-aircraft formations), the potential fuel savings for the long-haul route network for South African Airlines were estimated. The potential fuel burn reduction was 5.8%.

While Xu et al.[39] speculate that single-airline formation flight is likely to be easier, they also simulated multi-airline formation flight implementation. Taking the transatlantic Star-alliance as a case study, 7.7% of overall fuel savings were found.

Optimal Routing and Assignment for Commercial Formation Flight

Kent[40] also presented a transatlantic case study, reporting fuel savings of around 8.7% and 13.1% for two-aircraft and three-aircraft formations respectively.

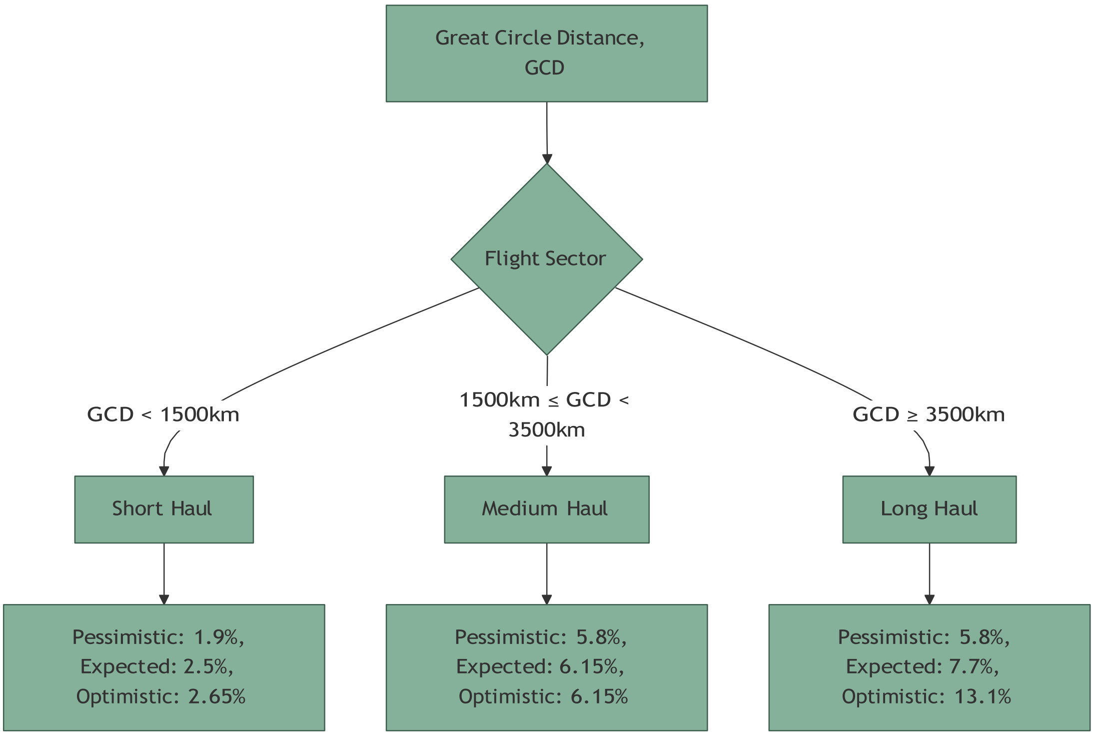
A further case study was also conducted for Singapore Airlines, to examine medium and long-haul routes. The potential savings here found to be 6.15%, decidedly lower than the transatlantic case study. This supports the case for cross-airline collaboration to facilitate bigger fuel savings.

Kent also had a case study on EasyJet European flights, as a way of investigating the impact of formation flight on low-cost carrier airlines which typically operate over short-haul routes. The overall saving for the EasyJet fleet was found to be 1.89%. This is decidedly less than that obtained for Long-haul flights. A contributing factor behind this was found to be that only 45% of the flights could be in formation, reducing the average fuel saving for the fleet. This is in contrast to the cases for the transatlantic case and for Singapore Airlines which could have 80-100% of flights in formation.

Energy-Efficient Path Planning for Commercial Aircraft Formation Flights

Curtis et al. [41] found that total fuel consumption decreased by 2.5-2.65% for a short-haul flight for the Melbourne to Sydney route. This is roughly in alignment for short-haul routes as found by Kent [40].

Figure 17: Summary of Literature on Efficacy Factors



The modelling architecture does not support range-dependent efficacy factors. The distance flown (flight-km) distributions for regional, narrowbody and widebody aircraft were used to determine the share of distance flown in the short-haul (32%), medium-haul (30%) and long-haul (38%) categories[42], and this in turn is used to calculate representative (weighted average) efficacy factors for the scenarios. The pessimistic efficacy factor is 0.68, and the expected efficacy factor is 0.83. The technical limits for each range category remain the same.

Assumption: It is assumed that the fuel burn due to speed deviation or extended holding to accommodate rendezvous of aircraft is negligible compared to the fuel saving achieved during formation flight.

Assumption: Future aircraft may feature higher aspect ratio wings than the current fleet through technologies such as truss-bracing or folding tips. This will reduce the induced drag for solo aircraft, which may reduce the strength of their upwash and thus diminish the benefits of formation flight, effectively reducing the technical limit fuel burn reduction. As the project is based around the existing fleet, this effect is not included in the model.

Note: The fuel savings were calculated on a fleet basis, by already considering the percentage of flights able to undertake formation flight. Therefore, it is not possible to separate efficacy and rollout rate.

Rollout

The technology and procedure development required to facilitate safe and robust formation flight is likely to be a long process. The AIA does not expect significant adoption by 2050, given the need for advanced navigation, communication and control systems. It is difficult to forecast the potential rollout beyond this date with certainty, so in the pessimistic and expected case, the adoption remains at zero.

In the optimistic scenario, a concerted effort would be made to enable formation flight as soon as 2040. The AIA believes the ICAO estimate [43] of 30% of flights participating in formation flight by 2070 in this case.

References

[38] Will Graham and Holger Babinsky. *3A1 Applications I: Aerofoils and Wings*. en. 2025.

[39] Jia Xu et al. "Aircraft Route Optimization for Formation Flight". In: *Journal of Aircraft* 51.2 (2014). Publisher: American Institute of Aeronautics and Astronautics _eprint: https://doi.org/10.2514/1.C032154, pp. 490–501. ISSN: 0021-8669. DOI: 10.2514/1.C032154. URL: https://doi.org/10.2514/1.C032154 (visited on 02/06/2025).

[40] Thomas Kent. "Optimal Routing and Assignment for Commercial Formation Flight". en. PhD thesis. University of Bristol, July 2015. DOI: 10.13140/RG.2.2.27277.74721. URL: https://tomekent.com/FormationFlight/papers/Kent2015Thesis.pdf.

[41] Olivia Curtis et al. "Energy-Efficient Path Planning for Commercial Aircraft Formation Flights". en. In: *Engineering Proceedings* 80.1 (2025). Number: 1 Publisher: Multidisciplinary Digital Publishing Institute, p. 15. ISSN: 2673-4591. DOI: 10.3390/engproc2024080015. URL: https://www.mdpi.com/2673-4591/80/1/15 (visited on 02/10/2025).

[42] *FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts*. URL: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf (visited on 02/20/2025).

[43] International Civil Aviation Organization (ICAO). *ICAO LTAG Report – Appendix M4*. Tech. rep. ICAO, 2022. URL: https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM4.pdf.

7.6 Single Engine Taxiing

At airports, aircraft landing and take-off (LTO) operations are major contributors to emissions. This documentation focuses on the single engine taxiing (SET) mitigation strategy.

Single engine taxiing is a procedure through which only half of the installed number of engines are used for taxiing operations, offering opportunities for fuel burn reduction [44].

7.6.1 Review of Single-Engine Taxiing from Literature

Note: The fuel saving percentages reported in this section are with respect to taxiing fuel only.

Assessing the environmental impact of aircraft taxiing technologies

Camilleri and Batra [45] find that single engine taxiing results in roughly 20% reduction in taxiing fuel consumption in comparison to full engine taxiing (FET). They acknowledge that this is roughly in alignment with the 30% quota within other literature.

Calculation and analysis of new taxiing methods on aircraft fuel consumption and pollutant emissions

Cao et al. [46] provide a comparison of fuel consumptions between FET and SET for different aircraft types. The percentage reduction computed for the selected aircraft are shown below:

Aircraft Type	Fuel Consumption Reduction due to SET (%)
A319	29.6
A320	29.6
A321	30.2
A330	33.3
B737	29.4
B738	29.5

Of these aircraft types, there is broad consistency in the impact of SET. A330s are typically used in long-haul flights and has slightly larger fuel savings proportionally in comparison to the other short-to-medium range aircraft.

Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports

Di Mascio et al. [47] segregate the analysis to be able to determine the impact of SET on taxi-in and taxi-out operations separately.

They find that taxi-out operations can achieve fuel savings of 30.2%, which is broadly in agreement with Cao et al[46]. The taxi-in operations can achieve fuel savings of roughly 10.1%. These differences in fuel savings make intuitive sense given that taxi-in uses lower thrust settings as they are decelerating as they make the journey back to the gate.

The impact of single engine taxiing on aircraft fuel consumption and pollutant emissions

In this study, Stettler et al. [44] find that minimizing the time before SET initiation results in taxi-in fuel reductions of 3-12%. Moreover, if the engine thrust level is minimized at the lowest operational thrust, the savings range from 8-15%. This figure is broadly in agreement with Di Mascio et al. [47].

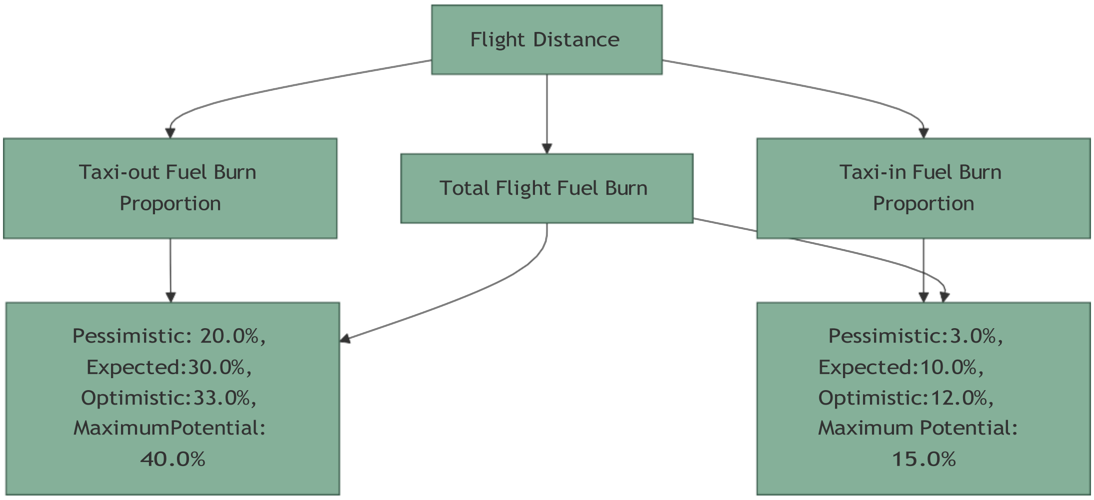
Evaluation of Strategies for Reducing Taxi-out Emissions at Airports

Deonandan and Balakrishnan [48] suggest that a theoretical reduction of 40% in taxi-out fuel burn is possible. This is greater than the other fuel savings mentioned within the literature, indicating a theoretical maximum saving.

7.6.2 Model Overview

This diagram shows how the fuel saving from single engine taxiing is estimated:

Figure 18: Estimating Fuel Savings from Single Engine Taxiing



The efficacy factors in the diagram are derived from the literature review conducted in the previous section. The expected case is based on the most commonly occurring values from within the literature, thus representing a central estimate. The pessimistic and optimistic scenarios reflect the lower and upper bounds respectively of the estimates obtained from literature, ensuring that a comprehensive range of potential impact can be covered. The technical limits stem from the most optimistic theoretical estimates, which are likely not realizable in reality, given operational constraints and aircraft-specific limitations.

7.6.3 Review of Rollout

Single engine taxiing (SET) is currently in use across many airports. Stettler et al.[44] reported that SET is regularly implemented at Heathrow Airport for taxi-in operations. However, despite this, SET is not as easy to implement widely and frequently as it seems. SET changes the maneuverability and balance of the aircraft, meaning that it cannot easily be used in poor weather conditions (such as heavy rain, wind or low visibility). In addition, due to the maneuverability aspect, it is not possible on certain geometries of taxiways, such as those which have slopes and multiple turns[49].

Taking the factors above into consideration, a pessimistic scenario would consider single-engine taxiing as the sole operational solution deployed for taxiing. Full rollout cannot be achieved for SET given the technical feasibility of the measure. The AIA thus assumes a 50% rollout by 2045 in the pessimistic case. The expected case, however, assumes that SET is to be used in conjunction with a higher efficacy engineless solution such as electric tugs. This case thus assumes lower rollout of SET, given the focus would be on electric tugs. In the optimistic case, SET is not included since it is assumed that airports will focus solely on higher efficacy solutions (i.e. electric tugs).

There are currently no specific regulations from the UK Civil Aviation Authority mandating SET but operators are required to ensure safe taxiing procedures[50]. Given that there are no legal requirements enforcing SET, the decision is left to individual airlines, based on operational feasibility and manufacturer recommendations.

References

[44] M. E. J. Stettler et al. "The impact of single engine taxiing on aircraft fuel consumption and pollutant emissions". en. In: *The Aeronautical Journal* 122.1258 (Dec. 2018), pp. 1967–1984. ISSN: 0001-9240, 2059-6464. DOI: 10.1017/aer.2018.117. URL: https://www.cambridge.org/core/product/identifier/S0001924018001173/type/journal_article (visited on 01/23/2025).

[45] Robert Camilleri and Aman Batra. *Assessing the environmental impact of aircraft taxiing technologies*. International Council of the Aeronautical Sciences, Sept. 2021. URL: https://www.icas.org/icas_archive/ICAS2020/data/papers/ICAS2020_1162_paper.pdf.

[46] Feng Cao et al. "Calculation and analysis of new taxiing methods on aircraft fuel consumption and pollutant emissions". In: *Energy* 277 (Aug. 2023), p. 127618. ISSN: 0360-5442. DOI: 10.1016/j.energy.2023.127618. URL: https://www.sciencedirect.com/science/article/pii/S0360544223010125 (visited on 01/24/2025).

[47] Paola Di Mascio et al. "Optimization of Aircraft Taxiing Strategies to Reduce the Impacts of Landing and Take-Off Cycle at Airports". en. In: *Sustainability* 14.15 (Jan. 2022). Number: 15 Publisher: Multidisciplinary Digital Publishing Institute, p. 9692. ISSN: 2071-1050. DOI: 10.3390/su14159692. URL: https://www.mdpi.com/2071-1050/14/15/9692 (visited on 01/24/2025).

[48] Indira Deonandan and Hamsa Balakrishnan. "Evaluation of Strategies for Reducing Taxi-out Emissions at Airports". en. In: *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*. Fort Worth, Texas: American Institute of Aeronautics and Astronautics, Sept. 2010. ISBN: 978-1-62410-159-5. DOI: 10.2514/6.2010- 9370. URL: https://arc.aiaa.org/doi/10.2514/6.2010- 9370 (visited on 01/24/2025).

[49] Guiseppe Pillirone. *Greener Aircraft Taxiing: Single-Engine Taxi-out Evaluations*. URL: https://www.sesarju.eu/sites/default/files/documents/webinars/Guiseppe.pdf (visited on 02/20/2025).

[50] CAA. *AMC1 SPO.GEN.119 Taxiing of aircraft*. 2012. URL: https://regulatorylibrary.caa.co.uk/965-2012/Content/AMC%20GM%204/AMC1%20SPO%20GEN%20119%20Taxiing%20of.htm (visited on 02/20/2025).

7.7 Electric Tugs - External Electric Taxiing Systems

Electric Tugs are an example of external electric taxiing systems - the aircraft uses semi-robotic or electric tow vehicles like TaxiBot during taxiing operations.

7.7.1 Advantages and Disadvantages of External Electric Taxiing Systems

Advantages	Disadvantages
No aircraft modification - facilitates certification process	Greater airport congestion due to greater numbers of towing vehicles
No extra mass added	Limited speed - potential lengthening of taxi times

7.7.2 Review of Electric Tug Efficacy Rates within Literature

Review, Challenges, and Future Developments of Electric Taxiing Systems

Lukic et al.[51] reviewed a number of technologies for electric taxiing systems.

TaxiBot is a hybrid (diesel)-electric tractor which tows aircraft throughout ground operations all the way to the runway, controlled by the pilot. Lukic et al. report a taxiing fuel reduction figure of 98%.

Green taxiing solution at Delhi Airport

Muthukrishnan and Ahmed[52] note that the use of TaxiBot as a "green taxiing" solution resulted in savings of around 230-260 liters of fuel per aircraft per taxiing event. This study assumed an average time of 14 minutes for TaxiBot usage.

Assuming the average taxiing time is the same, the fuel attributed to conventional taxiing can be given through:

$$F_{taxi} = N_{eng}\dot{m}_{taxi}t_{taxi} \tag{14}$$

Assuming a density of 0.804 kg/L for Jet-A1[53], fuel saving is between 185-210 kg.

Aircraft Type	Engine Type	Engine Fuel Flow Rate (kg/sec)[26]	Number of Engines	Taxi Fuel Burn (kg)
B737-700	CFM56-7B26	0.113	2	189.84
B737-800	CFM56-7B27	0.116	2	194.88
A319	CFM56-5B7	0.102	2	171.36

Using the aircraft above (which are part of the fleet compliant with TaxiBot), it is clear to see that efficacy rates can vary from 95% to 100%, given that total conventional taxiing fuel consumptions vary from being just above the savings range shown above or even below the average savings.

Assumption:

A larger fleet was trialled with TaxiBots at Indira Gandhi International airport (which is where Muthukrishnan and Ahmed conducted their study). For a first order estimate, the aircraft above were chosen as representative of the types compliant with TaxiBot regulations. Further detailed mod- eling could be done on a fleet basis.

Warning: To avoid confusion, since it appears that from this analysis that conventional taxi fuel usage is using less fuel than TaxiBot is predicted to save, the following clarifications are provided:

- The predicted fuel saving through TaxiBot (185-210 kg) is likely an average figure, calculated from the overall fleet, where the savings may vary between different aircraft. This cannot be accounted for in the table above, where we have used aircraft that are primarily used for short- to-medium haul flights. Longer-haul flights tend to have greater fuel flow rates for the same taxiing thrust setting which would result in a larger absolute fuel burn for taxiing than the range presented within the table. It is hard to account or provide an average estimate for conventional taxiing fuel consumption given that we do not have a detailed view of the fleet at Delhi airport.

TaxiBot

Smart Airport Systems[54] suggest that the efficacy of TaxiBot is around 85%.

Summary of Literature Review

Following on from literature review, the following optimisms for efficacy are thus proposed:

Optimism	Efficacy (%)
Pessimistic	85
Expected	95
Optimistic	100

7.7.3 Review of Rollout rates

It is important to note that EASA certified TaxiBots for narrowbody (short and medium-haul) aircraft, namely Boeing 737 and the Airbus A320 family in 2014[51], when it was introduced to Frankfurt Airport.

In 2022, Muthukrishnan and Ahmed[52] reported that 2 TaxiBots were operational at IGI airport, handling about 30-40 aircraft movements. Additionally, plans were in place to add 15 more TaxiBots by 2025, giving the capacity to handle 255-340 aircraft movements a day. In 2024, there were around 442,490 aircraft movements[55], giving a daily average of around 1200 aircraft movements. This shows that in 2025, around 20-28% of aircraft can be supported using electric tugs. A similar rollout rate could be assumed for other airports.

In the AIA's scenario analysis for rollout, the pessimistic case assumes that electric tugs will not be deployed. The expected case projects a slower adoption rate than observed at IGI Airport in Delhi, leading to a 50% rollout by 2040. In contrast, the optimistic scenario anticipates a faster deployment than the Delhi case study, achieving full adoption by 2035. This technology has already been certified by EASA and is in place (even if it is in a testing phase) in a few different airports[56]. At John F. Kennedy International Airport (JFK), preparations are underway to introduce external electric taxiing systems like TaxiBot[57]. Given that airports are actively considering the implementation of these external electric taxiing solutions, the assumption of more aggressive rollouts is reasonable. The growing interest is indicated through these pilot programs, meaning that adoption of tugs is gaining further momentum, especially over onboard electric taxiing systems which require years of aircraft recertification.

7.7.4 Nomenclature

Symbol	Definition	Unit
Γ_{taxi}	Fuel consumption for the taxiing phase	kg
N_{eng}	Number of Engines	-
$\dot{m}_{taxi}$	Engine Fuel Flow rate	kg/s
t_{taxi}	Time taken for taxiing operations	s

References

[26] *ICAO Aircraft Engine Emissions Databank | EASA*. en. URL: https://www.easa.europa.eu/en/domains/environment/icao-aircraft-engine-emissions-databank (visited on 01/27/2025).

[51] Milos Lukic et al. "Review, Challenges, and Future Developments of Electric Taxiing Systems". In: *IEEE Transactions on Transportation Electrification* 5.4 (Dec. 2019). Conference Name: IEEE Transactions on Transportation Electrification, pp. 1441–1457. ISSN: 2332-7782. DOI: 10.1109/TTE.2019.2956862. URL: https://ieeexplore.ieee.org/document/8918079/ (visited on 01/31/2025).

[52] M Muthukrishnan and Rekibuddin Ahmed. "Green taxiing solution at Delhi Airport". en. In: *ICAO* (2022). URL: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ENVReport2022_Art40.pdf.

[53] Third Wave Digital. *Commercial Jet Fuels | Sunoco LP*. en. URL: https://www.sunocolp.com/segments/commercial-jet-fuel (visited on 01/31/2025).

[54] *TaxiBot®*. en-US. URL: https://www.smart-airport-systems.com/solutions/taxibot/ (visited on 01/31/2025).

[55] *Delhi Airport: total aircraft movements 2024*. en. URL: https://www.statista.com/statistics/1490815/delhi-airport-total-aircraft-movements/ (visited on 01/31/2025).

[56] Wind River. *2297-TaxiBot-customer-success-story*. 2018. URL: https://www.windriver.com/themes/Windriver/pdf/2297-TaxiBot-customer-success-story.pdf (visited on 02/20/2025).

[57] Amanda Kwan. *At JFK, Preparations Under Way for 'Super Plane Tug'*. en. 2024. URL: https://www.panynj.gov/content/port-authority/en/blogs/air/at-jfk--preparations-under-way-for--super-plane-tug-.html (visited on 02/20/2025).

7.8 Electric Taxi

This document discusses onboard electric taxiing systems (ETS). These are systems which are integrated into the aircraft, consisting of installed electric motors which draw power from the APU. Thus main engines are not required to be used during this taxiing procedure.

Note: This measure has been documented for educational purposes. It is not expected to be favoured over other electric taxiing systems, such as the use of electric tugs. Whilst this is discussed extensively in the rest of this section, the primary reason for this involves the added weight of the onboard taxiing system, which requires recertification of aircraft, resulting in longer implementation timelines.
The scenario-based efficacies and rollout discussion is still included for completeness.

7.8.1 Advantages and Disadvantages of Onboard Electric Taxiing Systems

Advantages	Disadvantages
No need for reliance on ground support equipment	Added mass
Faster turnaround periods (faster relative to electric tug usage, but only slightly slower than conventional taxi)	Certification timelines

The use of onboard electric taxiing systems invites aircraft autonomy and decreased dependence on ground support equipment. This could result in faster turnaround times, increasing airport efficiency, but modeling this is considered out of scope for this sprint given that turnaround periods are outside the boundary of the analysis (which starts with taxiing operations). However, major challenges of onboard systems come from the aspect of added mass of the electrical motors and other components. This contributes to reduced indirect fuel savings during flight. Furthermore, onboard systems involve aircraft design changes which then require certification.

7.8.2 Review of Electric Tug Efficacy Rates within Literature

Review, Challenges, and Future Developments of Electric Taxiing Systems

Lukic et al.[51] reviewed a number of onboard taxiing technologies, namely WheelTug, Electric Green Taxiing System (EGTS) and Safran Onboard ETS. The characteristics of these systems are shown below:

Criteria	WheelTug	EGTS	Safran
System Configuration	Nose Landing Gear	Main Landing Gear	Main Landing Gear
Onboard Added Mass (kg)	130-140	400	320-380
Fuel Savings	50% of taxi fuel	3% of total fuel*	4% of total fuel*

Note:
* From literature, it is unclear where the block fuel saving figures for the EGTS and Safran technologies come from. The range of flight has not been specified and it is known that the taxiing fuel burn correlates to the flight range, as outlined in Taxiing Operations.

From Lukic et al.[51], it is important to note that the EGTS was terminated in 2016. WheelTug offers fuel savings as a percentage of conventional taxiing fuel consumption, as detailed in Taxiing Operations. Based on this method, the estimated reduction in block fuel ranges from 1.26% for flights of 10,000 km to 8.6% for flights of 350 km. These figures are broadly consistent with the block fuel savings reported for other e-taxiing solutions.

Lukic et al.[51] also discuss block-fuel reductions for a range of flight distances. The range of fuel savings was from around 1-7.4% for flight distances ranging from 250-2000 nautical miles (460-3700km). This is in line with the fuel reductions hypothesized previously. The difference can be accounted for due to the assumption made in the paper that total taxi time is roughly 22 minutes.

Statistical Approach for Electric Taxiing Requirements for Regional Turboprop Aircraft

Taltaud et al.[58] expect fuel savings of around 3.1% for the whole flight due to electric taxiing. This is for a turboprop aircraft (thus a short-haul flight). This is also roughly in alignment with findings from other literature studies.

Summary of Literature Review

By evaluating the literature above, a WheelTug fuel reduction factor of 50% (relative to conventional taxiing fuel consumption) is used in the model. This figure aligns with findings from other studies across various flight distances.

Optimism	Efficacy (%)
Pessimistic	50.0
Expected	62.5
Optimistic	75.0[59]

7.8.3 Review of Rollout Rates

Of the technologies mentioned by Lukic et al.[51], WheelTug is the only one expected to be certified and enter into service by 2026[60]. The European Union Aviation Safety Agency (EASA) does not yet have any specific regulations for onboard taxiing systems like WheelTug. The AIA assumes that, given the extensive recertification process required for these systems, airlines are more likely to opt for other electric taxiing solutions such as electric tugs. Given this reasoning, this measure is thus omitted from the scenario analysis for taxiing measures. The measure has been documented for educational purposes.

References

[51] Milos Lukic et al. "Review, Challenges, and Future Developments of Electric Taxiing Systems". In: *IEEE Transactions on Transportation Electrification* 5.4 (Dec. 2019). Conference Name: IEEE Transactions on Transportation Electrification, pp. 1441–1457. ISSN: 2332-7782. DOI: 10.1109/TTE.2019.2956862. URL: https://ieeexplore.ieee.org/document/8918079/ (visited on 01/31/2025).

[58] Alexandre Taltaud et al. "Statistical Approach for Electric Taxiing Requirements for Regional Turboprop Aircraft". In: *Journal of Aircraft* 60.6 (2023). Publisher: American Institute of Aeronautics and Astronautics _eprint: https://doi.org/10.2514/1.C037090, pp. 1811–1818. ISSN: 0021-8669. DOI: 10.2514/1.C037090. URL: https://doi.org/10.2514/1.C037090 (visited on 02/04/2025).

[59] Denzil Neo. "Alternatives to Reducing Aviation Fuel-Burn with Technology: Fully Electric Autonomous Taxibot". en. In: *Student Works* (2023).

[60] Matthew Davies. *WheelTug: Helping aircraft taxi to a cleaner future*. en. URL: https://www.thenationalnews.com/climate/road-to-net-zero/2024/05/17/wheeltug-helping-aircraft-taxi-to-a-cleaner-future/ (visited on 02/04/2025).

7.9 Mass Reduction

7.9.1 Introduction

This measure models the fuel burn impact of cabin lightweighting for the existing aircraft fleet, as opposed to the impact of structural efficiency improvements applied in future aircraft designs (out of scope).

Mass reduction reduces the required lift the aircraft must produce to remain aloft. Assuming that the lift to drag ratio is approximately constant, reducing lift decreases the total drag. In turn, the required thrust is reduced. Assuming also that the engine overall efficiency is approximately constant with thrust demand, the fuel burn is also reduced. Both of these assumptions are reasonable for an aircraft operating close to its design conditions.

7.9.2 Impact

An ATI report on cabin weight reduction[61] details expected possible reductions for the different cabin components of an Airbus A320.

Item	2020 mass (kg)	2030 mass target (kg)	2020-2030 mass reduction
Seats	1,601	1,290	20%
Linings	363	340	5%
Stowage bins	188	220	-20%
Passenger service unit (PSU)	172	130	20%
Services (lavatories and galleys)	563	450	20%
Insulation blankets	418	310	25%
Carpets	240	210	10%
Floor panels	376	330	10%
Total	**3,919**	**3,320**	**16%**

Assumption: The ATI report gives the cabin furnishings mass fraction $m_{furnishing}/m_{OE}$ of the A320 as 10% of the operating empty mass. As detailed airframe manufacturer/operator mass breakdown data is not publicly available due to commercial sensitivity, 10% is assumed to be applicable to all aircraft. Similarly, a 16% reduction in $m_{furnishing}$ is assumed to be applicable to all aircraft, such that all aircraft experience a 1.6% reduction in operating empty mass in the technical limit.

Note: It is observed that the mass of stowage bins is expected to increase between 2020 and 2030 according to the ATI report. Whilst the reason has not been specifically provided within the report, there are a number of factors which can contribute to this increase:

- Larger stowage bin sizes[62] - As airlines handle more carry-on baggage, there has been greater demand for increasing the volume and functionality of stowage bins, which may require reinforced structure to be able to handle the additional loads.
- Advanced mechanisms[62] - Integration of stowage bin lift assist mechanisms add functionality and comfort for passengers and cabin crew but possibly at the expense of added weight

The ATI expects the reduction in cabin mass to be achieved between 2020 and 2030. Assuming a linear rollout, the baseline year (2025) will have achieved 50% of this. Therefore, the technical limit is a 0.8% structural mass reduction (50% of the 16% cabin mass reduction, which is 10% of total aircraft mass).

7.9.3 Model

The mass reduction then needs to be translated into a fuel burn reduction.

The Breguet range equation may be written as:

$$\frac{m_{i,1}}{m_{f,1}} = e^{\frac{s}{H_1}} \tag{15}$$

Where $m_{i,1}$ is the aircraft start-of-phase mass and $m_{f,2}$ is the aircraft end-of-phase mass for the original flight, without cabin mass reduction, s is the phase air distance flown, and H_1 is the Breguet range parameter for the original flight.

For the flight with mass reduction:

$$\frac{m_{i,2}}{m_{f,2}} = e^{\frac{s}{H_2}} \tag{16}$$

The Breguet range parameter $H = \left(\frac{\eta_{ov} LCV\ (L/D)}{g}\right)$ is characteristic of the aircraft type (propulsion system, fuel and aerodynamics). A greater value of H enables an aircraft to fly greater distances with the same fuel mass fraction, so all else equal a higher value of the range parameter indicates a more efficient aircraft (although it does not include the structural performance of the aircraft).

Note that because the overall efficiency η_{ov} and lift to drag ratio (L/D) are constant, $H_1 = H_2$. Therefore:

$$\frac{m_{i,1}}{m_{f,1}} = \frac{m_{i,2}}{m_{f,2}} \tag{17}$$

The aircraft mass can be decomposed into the fuel, payload and operating empty mass:

$$\frac{m_{OE,1} + m_P + m_{F,i,1}}{m_{OE,1} + m_P + m_{F,f,1}} = \frac{m_{OE,2} + m_P + m_{F,i,2}}{m_{OE,2} + m_P + m_{F,f,2}} \tag{18}$$

Where $m_{OE,1}$ denotes the aircraft operating empty mass for the original flight, m_P is the payload mass and $m_{F,i,1}$ and $m_{F,f,2}$ are the start-of-phase and end-of-phase fuel masses for the original flight. As before, "$_2$" denotes the same quantities for the flight with mass reduction measures active. Note that as the direct fuel saving of the measure is needed, the initial phase fuel masses $m_{F,i,1} = m_{F,i,2}$ are equal. If solving to include the indirect fuel saving, the end-of-phase fuel masses would be equal instead.

A few relations which make it easier to relate the change in empty mass, Δm_{OE}, to the change in fuel burn, Δm_{FB}, are:

$$m_{OE,2} = m_{OE,1} - \Delta m_{OE} \tag{19}$$

$$m_{FB,1} = m_{F,i,1} - m_{F,f,1} \tag{20}$$

$$m_{FB,2} = m_{F,i,2} - m_{F,f,2} \tag{21}$$

$$m_{FB,1} - m_{FB,2} = m_{F,f,2} - m_{F,f,1} = \Delta m_{FB} \tag{22}$$

Equation 18 can be rearranged to find the ratio of fuel burns in terms of the change in structural mass:

$$f_{\text{mass reduction}} = \frac{\Delta m_{FB}}{m_{FB,1}} = \frac{\Delta m_{OE}}{m_{OE,1} + m_P + m_{F,i,1}} = \frac{\Delta m_{OE}}{m_{i,1}} \tag{23}$$

I.e. the fuel burn reduction is equal in proportion to the mass reduction. This leaves the payload mass and fuel mass as the only unknowns.

A typical payload mass of around 30% of the aircraft operating empty mass is assumed[63].

$$m_P = 0.30 m_{OE} \quad (24)$$

The time-average proportion of aircraft mass which must be fuel can be found using the Breguet range equation.

$$m_{r,\text{midcruise}} = \frac{1}{2}(m_{OE} + m_P)\left(1 - e^{-\frac{s}{H}}\right) \quad (25)$$

The range parameter H is estimated as a function of range. Thus, the total mass at midcruise (without cabin mass reduction) is:

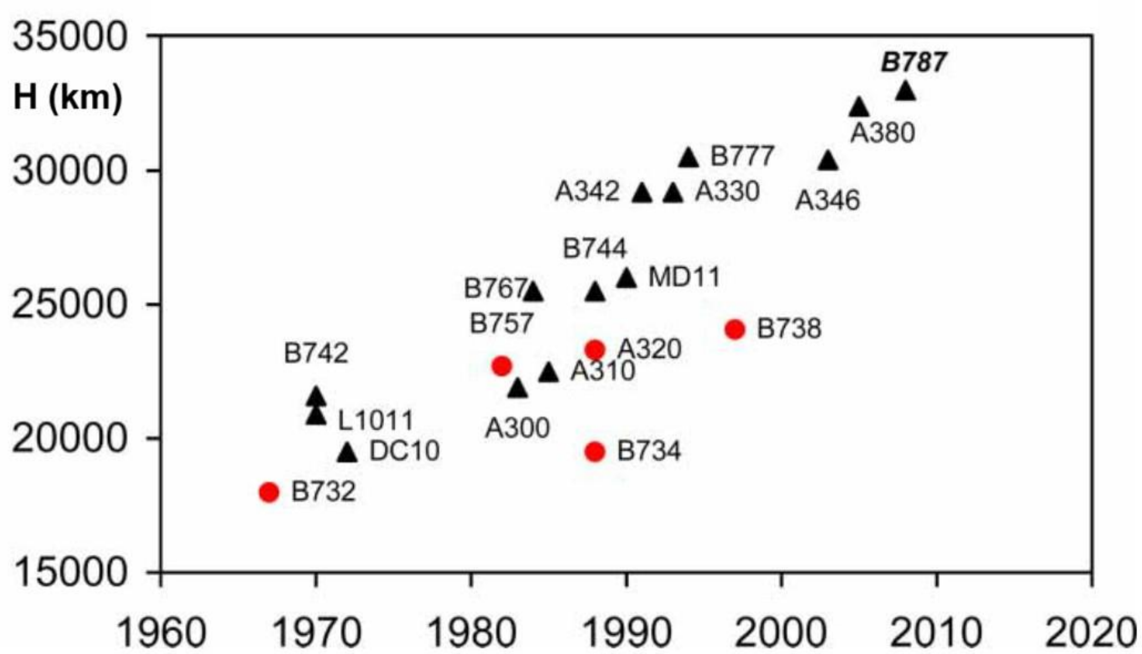
$$m_{\text{total,midcruise}} = m_{OE} + m_P + m_{r,\text{midcruise}} = 1.30 m_{OE}\left(1 + \frac{1}{2}\left(1 - e^{-s/H}\right)\right) \quad (26)$$

So with the mass reduced due to the lightweight cabin, the fuel burn reduction in the air can be expressed as:

$$f_{\text{mass reduction}} = \frac{\Delta m_{OE}}{1.30 m_{OE}\left(1 + \frac{1}{2}\left(1 - e^{-s/H}\right)\right)} \quad (27)$$

Note: Estimated values of the range parameter H are shown for select aircraft types, according to their entry into service year [64]. More recently developed aircraft tend to have greater range parameter values than older aircraft, and widebody aircraft tend to have greater range parameter values than narrowbody aircraft of a similar era.

Figure 19: Time evolution of the range parameter for narrowbody and widebody aircraft



Time evolution of the range parameter for narrowbody (red dots) and widebody (black triangle) aircraft. Adapted from R. Martinez-Val et al[64].

In this model, the explicit aircraft type for each flight is not known. Estimated effective values of the Breguet range parameter for short, medium and long-haul flights were created by the AIA. The estimates are based on approximate range parameters of aircraft types within the UK fleet used for each range category. The short, medium and long-haul boundaries are based on a CAA definition[7]. The UK aircraft fleet composition as of November 2024 was used, based on November 2024 CAA fleet data[65].

Flight length classification	Range	Estimated Breguet range parameter
Short-haul	$s < 1{,}500$ km	23,000 km
Medium-haul	$1{,}500 \text{ km} < s \leq 3{,}500$ km	25,000 km
Long-haul	$s \geq 3{,}500$ km	31,000 km

During taxiing, small reductions in mass will not materially reduce the engine fuel burn, as in these phases the engines are normally operating at idle throttle. The mass reduction fuel burn factor is therefore applied to climb, cruise and descent phases only.

7.9.4 Rollout

The efficacy and rollout cannot be easily separated for this measure.

- **Low Scenario:** 100% rollout for short-haul flights by 2040
- **Medium Scenario:** 100% rollout for short- and medium-haul flights by 2035
- **High Scenario:** 100% rollout for all flights by 2030

7.9.5 Limitations

ATI[61] notes that incremental mass reduction within aircraft cabins is increasingly difficult given that most cabin product designs are relatively matured and optimized. Strict certification requirements mean that manufacturers prefer to use proven designs and materials over taking the risk of new technology (even though it may introduce significant mass reduction by comparison). The costs of developing new lightweight materials can also be high, which is not favorable for airlines who are trying to keep costs low. The market's price sensitivity thus limits the impact that use of newer materials may have.

7.9.6 Nomenclature

7.9.7 Roman Symbols

Symbol	Definition	Unit
f	Fuel burn reduction factor	–
g	Acceleration due to gravity	m/s^2
H	Aircraft Breguet range parameter	m
LCV	Lower Calorific Value	J/kg
(L/D)	Lift-to-drag ratio	–
H	Breguet range parameter	km
m	Mass	kg
s	Flight great circle distance	km

7.9.8 Greek Symbols

Symbol	Definition	Unit
η_{ov}	Propulsion system overall efficiency	–

References

[7] CAA. *Cancellations | Civil Aviation Authority*. 2025. URL: https://www.caa.co.uk/passengers-and-public/resolving-travel-problems/delays-and-cancellations/cancellations/ (visited on 01/16/2025).

[61] Aerospace Technology Institute (ATI). *Sustainable Cabin Design*. Tech. rep. FZO-AIR-POS-0039. Aerospace Technology Institute (ATI), 2022. URL: https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIR-POS-0039-Sustainable-Cabin-Design.pdf.

[62] Bill Wilk, Ryan Evans Published October 12, and 2016. *Evolution of the aircraft stowage bin*. en. URL: https://www.aerospacemanufacturinganddesign.com/article/evolution-of-the-aircraft-stowage-bin/ (visited on 03/05/2025).

[63] Michael Husemann, Katharina Schäfer, and Eike Stumpf. "Flexibility within flight operations as an evaluation criterion for preliminary aircraft design". en. In: *Journal of Air Transport Management* 71 (Aug. 2018), pp. 201–214. ISSN: 09696997. DOI: 10.1016/j.jairtraman.2018.04.007. URL: https://linkinghub.elsevier.com/retrieve/pii/S0969699718301431 (visited on 02/20/2025).

[64] R Martinez-Val, J F Palacin, and E Perez. "The evolution of jet airliners explained through the range equation". en. In: *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 222.6 (June 2008). Publisher: IMECHE, pp. 915–919. ISSN: 0954-4100. DOI: 10.1243/09544100JAERO338. URL: https://doi.org/10.1243/09544100JAERO338 (visited on 01/30/2025).

[65] *UK airline data November 2024 | Civil Aviation Authority*. URL: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airlines/uk-airline-data/uk-airline-data-2024/november-2024/ (visited on 01/30/2025).

7.10 Aggregation Formulae

This section outlines the methodology for aggregating fuel savings to determine the overall savings from multiple operational efficiency measures. By systematically combining individual fuel saving estimates, we can quantify the cumulative impact of various strategies, ensuring a comprehensive evaluation.

7.10.1 Flight Phases

Operational efficiency measures impact specific phases of flight, meaning that aggregation of the fuel burn savings from different operational efficiency measures must first be done at the flight phase-level initially. As an example, single engine taxiing impacts the taxi-in and taxi-out phases, while formation flight is implemented during cruise.

Taxi-out

This phase includes taxiing mitigations (such as single engine taxiing or electric tugs) as well as APU Shutdown.

$$f_{taxi-out,overall} = (f_{taxi-out} \cdot f_{\text{APU Shutdown}}) \cdot P_{taxi-out,normalixed} \quad (28)$$

Climb

This phase includes continuous climb operations and mass reduction through lightweight aircraft cabins.

$$f_{climb,overall} = (f_{CCO} \cdot f_{\text{mass reduction}}) \cdot P_{climb,normalixed} \quad (29)$$

Cruise

This phase includes mitigating against horizontal, vertical and speed deviations in flight through 4D trajectory management, formation flight and mass reduction through lightweight aircraft cabins.

$$f_{cruise,overall} = (f_{\text{vertical deviation}} \cdot f_{\text{horizontal deviation}} \cdot f_{\text{speed deviation}} \cdot f_{\text{formation flight}} \cdot f_{\text{mass reduction}}) \cdot P_{cruise,normalixed} \quad (30)$$

Descent

This phase includes continuous descent operations and mass reduction through lightweight aircraft cabins.

$$f_{descent,overall} = (f_{CDO} \cdot f_{\text{mass reduction}}) \cdot P_{descent,normalixed} \quad (31)$$

Taxi-in

This phase includes taxiing mitigations (such as single engine taxiing or electric tugs) as well as APU Shutdown.

$$f_{taxi-in,overall} = (f_{taxi-in} \cdot f_{\text{APU Shutdown}}) \cdot P_{taxi-in,normalixed} \quad (32)$$

Combined Aggregation

All these phase fuel reduction factors are then combined:

$$f_{combined,overall} = f_{taxi-out,overall} + f_{take-off,overall} + f_{climb,overall} + f_{cruise,overall} + f_{descent,overall} + f_{taxi-in,overall} \quad (33)$$

Note: there are no operational efficiency measures to be applied at take-off, thus no formula is provided. $f_{take-off,overall}$ is expected to be 1.

7.10.2 Nomenclature

Symbol	Definition	Unit
$f_{phase,overall}$	Fuel reduction factor for a given flight phase, relative to total flight fuel burn	-
$f_{taxi-out}$	Fuel reduction factor for taxiing mitigations	-
$f_{\text{APU Shutdown}}$	Fuel reduction factor for APU Shutdown	-
f_{CCO}	Fuel reduction factor for continuous climb operations	-
$f_{\text{mass reduction}}$	Fuel reduction factor due to mass reduction	-
$f_{\text{vertical deviation}}$	Fuel reduction factor due to mitigations against vertical deviations	-
$f_{\text{horizontal deviation}}$	Fuel reduction factor due to mitigations against horizontal deviations	-
$f_{\text{speed deviation}}$	Fuel reduction factor due to mitigations against speed deviations	-
$f_{\text{formation flight}}$	Fuel reduction factor due to formation flight	-
f_{CDO}	Fuel reduction factor for continuous descent operations	-
$PP_{phase,normalixed}$	Proportion of the total flight fuel burn for that phase, normalized, as detailed in Empirical Fuel Burn Methodology	-
$f_{combined_overall}$	Overall fuel reduction factor	-

8 Costs

8.1 Operational Efficiency Measures

This document outlines the costs expected for each operational efficiency measure. The additional expenditure for each measure is outlined. Cost savings are a function of the efficiency of each measure, along with the price per unit of fuel.

Warning:

The costs within this document are based on those provided by ICAO[43]. The cost assumptions made in the report appear hard to interrogate given that the underlying methodology was not explicitly provided. While their estimates seem to be on the higher side, it is acknowledged that it can also be seen to account for unforeseen costs which can arise during implementation of these sustainable practices. Thus, for a high-level overview of costs, this is seen as an acceptable source, but there are obvious limitations, which are highlighted where necessary through admonition boxes in the rest of the section.

Assumption: The costs from ICAO are for the global aviation industry, assumed to be in terms of USD 2022 - unadjusted for the current year.

The following table explains why each measure affects ticket cost components:

Measure	Group	Aircraft	Airport	Air Traffic Control	Other (Airline)
APU Shutdown	Auxiliary Power Unit	-	PCA and GPU	-	-
Formation Flying	Drag Reduction	-	-	Extra Movements	Extra Crew
Single Engine Taxi	Taxiing	-	-	-	-
Electric Tugs	Taxiing	-	Charging Equipment	-	Electric Tugs
Electric Taxiing	Taxiing	-	-	-	E-Taxi Retrofit
Lightweight Cabin	Mass Reduction	-	-	-	Cabin Refurbishment

8.1.1 Air Traffic Management

The costs associated with air traffic management are highly uncertain and typically reported in literature under diverse categories. In general, it would be expected that there would be an increase from Air Navigation Service Providers (ANSPs). Whilst ANSPs may increase their base rate to cover temporary costs such as staff re-training, or other operational costs such as greater maintenance and communication links, there is little consensus on the true cost of these required investments.

The following costs, estimated by ICAO [43], might be incurred under the umbrella of air traffic management.

Warning: It should be noted that the link between these measures and the fuel savings they provide is unclear. It is also possible that some double-counting may have occurred within this analysis by ICAO and hence the total cost of the different measures is likely an overestimate.

Measure	Cost Category	Low (USD B)	Mid (USD B)	High (USD B)
Dynamic Sectorization	ATC	3.4	10.7	20.1
In-trail procedure (ITP)	ATC	0.08	0.42	0.76
In-trail procedure (ITP)	Airline	0.4	1.9	3.4
Optimized Runway Delivery Support tool and Reduced Pair-Wise Weather Dependent Separation between Arrivals	ATC	0.9	1.4	2.2
Support for Optimized Separation Delivery and Reduced Pair-Wise Weather Dependent Separation between Departures	ATC	0.9	1.4	2.2
Geometric Altimetry and RVSM Phase 2	ATC	0.7	1.4	2.1
Geometric Altimetry and RVSM Phase 2	Airline	3.9	7.8	11.7
Global Air Traffic Management	ATC	0.9	1.5	2.3
Total		10.28	25.12	44.46

Warning: The "Low", "Mid" and "High" cost scenarios represent the scenario modelling utilized within the ICAO report. It is unclear exactly which assumptions regarding policy, rollout and technology these scenarios are pinned on, but nevertheless these represent the possible range in costs for these measures, in order to highlight the uncertainty.

Warning: The "Low", "Mid" and "High" cost scenarios represent the scenario modelling utilized within the ICAO report. It is unclear exactly which assumptions regarding policy, rollout and technology these scenarios are pinned on, but nevertheless these represent the possible range in costs for these measures, in order to highlight the uncertainty.

8.1.2 Auxiliary Power Unit

APU Shutdown

This measure replaces the APU usage with preconditioned air and ground power units. The costs of this measure are expected to be primarily associated with the airport. The following table is extracted from ICAO[43]:

Cost Category	Low (USD B)	Mid (USD B)	High (USD B)
Airport	3.4	4.3	5.2

Within the model, it is assumed that the airport costs for this measure are linearly amortized over a 30 year period.

The installation of PCA units and GPU systems represents a multi-billion-dollar investment for airports. Airports are able to recover some of this cost through higher airport fees or specific PCA/GPU usage fees for airlines. The general directorate of state airports in Türkiye (which represent both major regional and small regional airports) published a document[66] outlining charges for PCA units and GPU usage on a per-minute basis for various categories of maximum take-off weight (MTOW).

Heathrow airport[67] (which is a suitable representation for intercontinental hub airports) bills electricity consumption due to use of FEGP systems on a per kilowatt-hour (kWh) basis. This is enforced through the use of automatic meter readings. The price at Heathrow airport is 0.43 GBP per kWh for the period 1 January - 31 December 2025. A similar pricing structure exists for the use of PCA units[67], with a current unit price of 1.00 GBP per kWh as a discretionary rate, but Heathrow further report that this price structure led to an under-recovery of 18.6 million GBP. This implies future price increases, with Heathrow reserving the right to adjust PCA charges to align with actual costs. This could potentially further impact cost structures, leading to marginally higher prices. On the other hand, the APU burns kerosene quite inefficiently, so switching to PCA and FEGP significantly reduces fuel consumption. While airlines pay a fee for their usage, the total energy cost is lower.

The above outlines how pricing structures may vary from airport to airport, and thus may impact the cost incurred by aircraft operators.

8.1.3 Drag Reduction

Formation Flying

The costs for formation flying are expected to be in two areas: air traffic control due to the additional aircraft movements and the airline due to additional crew and therefore labor costs. The following table is extracted from ICAO[43]:

Cost Category	Low (USD B)	Mid (USD B)	High (USD B)
Air Traffic Control	1.0	2.4	4.7
Airline (other)	21	27	34

Warning: It is unclear whether the costs here correspond to the maximum adoption listed, which was 30% of flights, or are representative global costs for 100% uptake.

The ATC certification costs for formation flying which range from 1.0-4.7 billion USD represents a one-time investment (not to remain once all aircraft have been recertified), which may cover the cost of new training programs, and upgrades to ATC infrastructure to facilitate the added demand and complexities of formation flight. Certification efforts would require regulatory approvals alongside integration of new technologies for improved ATC systems.

On the airline side, both fixed and variable costs are encountered. ICAO seems to be including variable costs on a per-year basis for airlines. Fixed costs could stem from investments into training programs for pilots and crew but these have not been accounted for by ICAO. Variable costs (covered by ICAO) are assumed to cover the increased crew wages (since ICAO believe extra crew will be required), adjustments in scheduling (including impact on passengers for changes in flight departure/arrival times for grouped flights) and other operational complexities of facilitating flying in close proximity.

8.1.4 Taxiing Operations

Single Engine Taxiing

Single engine taxiing appears to require zero additional expenditure. Literature[68] comparing dual engine taxiing, single engine taxiing and e-tugs implies that the single engine case does not increase any other costs.

It is reported that the lack of use of single-engine taxiing is due to a number of reasons. A pilot survey[69] found that some associated issues are excessive thrust, maneuverability problems during bad weather, second engine startup and general distractions. This is better reflected in the adoption rate within the model.

Electric Tugs

The costs for electric tugs are expected to be in two areas: airport due to the additional charging requirements and the airline in order to purchase the fleet of tugs. The following table is extracted from ICAO[43]:

Cost Category	Low (USD B)	Mid (USD B)	High (USD B)
Airport	-	2.4	-
Airline (other)	18.2	25.1	32.0

The main uncertainty here is the number of tugs that would be required. Another report[68] stated the cost of a tug was 1.5 million USD each. Based on this value, it appears as though ICAO are expecting between 12,000 and 21,000 tugs to be required. This would equate to approximately one tug per three aircraft globally.

Assumption: It is assumed that airline costs from ICAO refer to absolute costs of electric tugs, rather than the additional costs associated with electric tugs relative to diesel tugs.

These costs represent fixed costs incurred by the airport and airlines. Similar to APU shutdown, airports could recover some of the cost through charging for electricity consumption, similar to the pricing structure for the use of FEGP systems, which represent variable costs for airlines.

Electric Taxiing

Electric taxiing costs are associated with retrofitting the e-taxi system onto existing aircraft. It is relatively unclear what the costs of this would be, with one report[68] stating that the installed cost would be between 250,000 and 1,000,000 USD per aircraft. Assuming these costs are associated with the airline, and all existing aircraft, of which there are approximately 28,398 according to Statista[70], the table outlines the expected costs:

Cost Category	Low (USD B)	Mid (USD B)	High (USD B)
Airline (other)	7.1	14.2	28.4

Note: The mid case here assumes an installed cost of 500,000 USD per aircraft.

8.1.5 Mass Reduction

Lightweight Cabin

This measure can consist of many retrofitted cabin changes which would reduce the overall mass of the aircraft.

One source[71] reported the unit cost change for lightweight economy class passenger seats. Costs were reported between 1400 and 2550 USD (2009) per seat, with installation costs at 50 USD per seat. Assuming 28,398 aircraft (Statista[70]), and approximately 150 seats per aircraft, the cost associated with replacing all aircraft seats globally can be calculated.

Cost Category	Low (USD B)	Mid (USD B)	High (USD B)
Airline (other)	8.7	12.3	15.9

8.1.6 Order of Magnitude analysis for the impact on ticket cost

The total costs reported above are in the order of 100 billion USD as a total investment to implement operational efficiency measures. It should be noted that these costs are likely one-off costs and additional recurring costs are likely to be required to maintain the operational measures. With fuel reductions ranging from 5-15%, the investment may save approximately 5-30 billion per year in fuel expenditure, although this figure does not take into account recurring costs, nor does it account for a possible increase in future fuel costs. Such net cost saving aligns with an economic analysis conducted by the London School of Economics which reported annual global cost savings around 5-15 billion USD[72].

The net cost savings of operational measures have also been reported by scientific literature and international institutions. Andreas Schafer reported that implementing operational efficiency measures should lead to negative marginal abatement costs (as low as -320 USD/tonne of CO_2)[73]. The negative marginal abatement costs were also reported by McKinsey[74].

Considering a total annual expenditure of 847 billion USD in 2023[75], the cost savings that would result from implementing operational efficiency measures (5-30 billion USD per year) would represent 0.5-3.5% of the industry's total expenses. Assuming 100% cost pass-through to consumers, the decrease in ticket price would be 0.5-3.5%. Such a small decrease in ticket price would probably be offset by the decrease in flexibility that operational efficiency measures would impose on the aviation operators, combined with the high uncertainty in realizing these savings consistently for all flights.

Note: It must be noted that the above figures are based on very preliminary analysis. Further deconstruction of airline balance sheets and ticket cost components would be required in order to ascertain how these measures translate into ticket cost changes.
Expected fuel savings are a function of future fuel expected costs and efficiencies, as outlined at the beginning of this cost documentation. With sustainable aviation fuel (SAF) expected to come in, it is reasonable to assume that the proportion of the ticket price attributed to fuel will increase. Thus cost savings due to fuel reductions may be higher than indicated.

References

[43] International Civil Aviation Organization (ICAO). *ICAO LTAG Report – Appendix M4*. Tech. rep. ICAO, 2022. URL: https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM4.pdf.

[66] Tarifeler Şube Müdürlüğü. *DHMI Airport Charges 2023*. en. Tech. rep. GENERAL DIRECTORATE OF STATE AIRPORTS AUTHORITY REPUBLIC OF TÜRKİYE, 2023. URL: https://www.dhmi.gov.tr/Lists/UcretTarifeleri/Attachments/64/2023_Airport_Charges.pdf.

[67] Heathrow. *General-Notice-01_25-Tariffs-with-effect-from-1-January-2025*. 2024. URL: https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/doing-business-with-heathrow/regulated-charges/2025/General-Notice-01_25-Tariffs-with-effect-from-1-January-2025.pdf (visited on 03/06/2025).

[68] Parth Vaishnav. "Costs and Benefits of Reducing Fuel Burn and Emissions from Taxiing Aircraft: Low-Hanging Fruit?" en. In: *Transportation Research Record: Journal of the Transportation Research Board* 2400.1 (Jan. 2014), pp. 65–77. ISSN: 0361-1981, 2169-4052. DOI: 10.3141/2400-08. URL: https://journals.sagepub.com/doi/10.3141/2400-08 (visited on 02/12/2025).

[69] *A survey of airline pilots regarding fuel conservation procedures for taxi operations*. en. 2010. URL: https://www.internationalairportreview.com/article/2582/a-survey-of-airline-pilots-regarding-fuel-conservation-procedures-for-taxi-operations/ (visited on 02/12/2025).

[70] *Aircraft fleet - number of airplanes in service 2034*. en. 2025. URL: https://www.statista.com/statistics/282237/aircraft-fleet-size/ (visited on 02/12/2025).

[71] Mattias Carlsson. "Cost-efficient light-weighting within the aviation sector". PhD thesis. Saint Louis University, 2009. URL: https://stud.epsilon.slu.se/10948/1/carlsson_m_170920.pdf (visited on 02/12/2025).

[72] Alexander Grous. *Sky High Economics - Chapter Two: Evaluating the Economic Benefits of Connected Airline Operations*. en-GB. 2018. URL: https://www.lse.ac.uk/business/consulting/reports/sky-high-economics-chapter-two.aspx (visited on 02/23/2025).

[73] Andreas W. Schäfer et al. "Costs of mitigating CO2 emissions from passenger aircraft". en. In: *Nature Climate Change* 6.4 (Apr. 2016). Publisher: Nature Publishing Group, pp. 412–417. ISSN: 1758-6798. DOI: 10.1038/nclimate2865. URL: https://www.nature.com/articles/nclimate2865 (visited on 02/23/2025).

[74] McKinsey. *Decarbonizing aviation: Executing on net-zero goals | McKinsey*. 2023. URL: https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/decarbonizing-aviation-executing-on-net-zero-goals (visited on 02/23/2025).

[75] IATA. *Industry Statistics*. en. Tech. rep. IATA, 2024. URL: https://www.iata.org/en/iata-repository/pressroom/fact-sheets/industry-statistics/.

9 Briefing Notes

9.1 Briefing Notes

This section includes two briefing notes. These notes offer an in-depth qualitative analysis of operational efficiency measures that, while relevant, were not incorporated into the dataset used for this work. The specific topics covered in the briefing notes were selected in consultation with the DfT, ensuring that they align with the broader goals of this analysis.

The following briefing notes have been prepared to aid understanding:

1. Wingtip Devices
2. Load Maximization

9.2 Load Maximization

Load maximization, in this briefing note, refers to the efforts to maximise the number of passengers an aircraft carries per flight. Load maximization is divided into two key components: (i) load factor and (ii) seat density

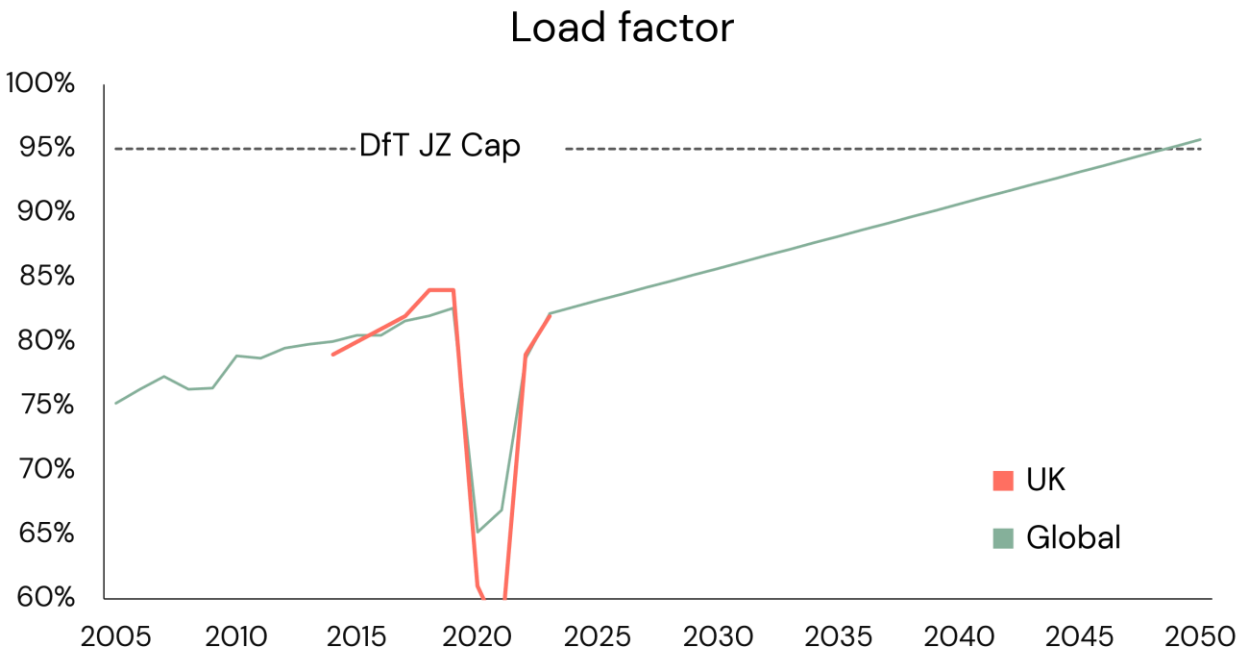
- **Load Factor** represents the percentage of available seating capacity that is occupied by paying passengers. It serves as a crucial performance metric for airline efficiency and profitability.
- **Seat Density** refers to the proportion of actual seats installed in an aircraft cabin relative to the maximum seating capacity the aircraft is certified for. It is a key indicator of how efficiently an airline configures its cabin space to maximise capacity.

We distinguish between load factor and seat density because they address different aspects of load maximization. **Load factor** is concerned with optimising passenger occupancy within a fixed seating configuration, relying on **operational and booking strategies**. In contrast, **seat density** focuses on modifying the aircraft's interior layout to accommodate more seats within a given aircraft design, requiring **structural reconfiguration**.

We acknowledge that some industry naming conventions group both of these aspects under the broader term "Load factor." However, for clarity in this analysis, we have chosen to differentiate between the two to better illustrate the distinct operational and design considerations involved in load maximization.

9.2.1 Load Factor

Figure 20: Load Factor

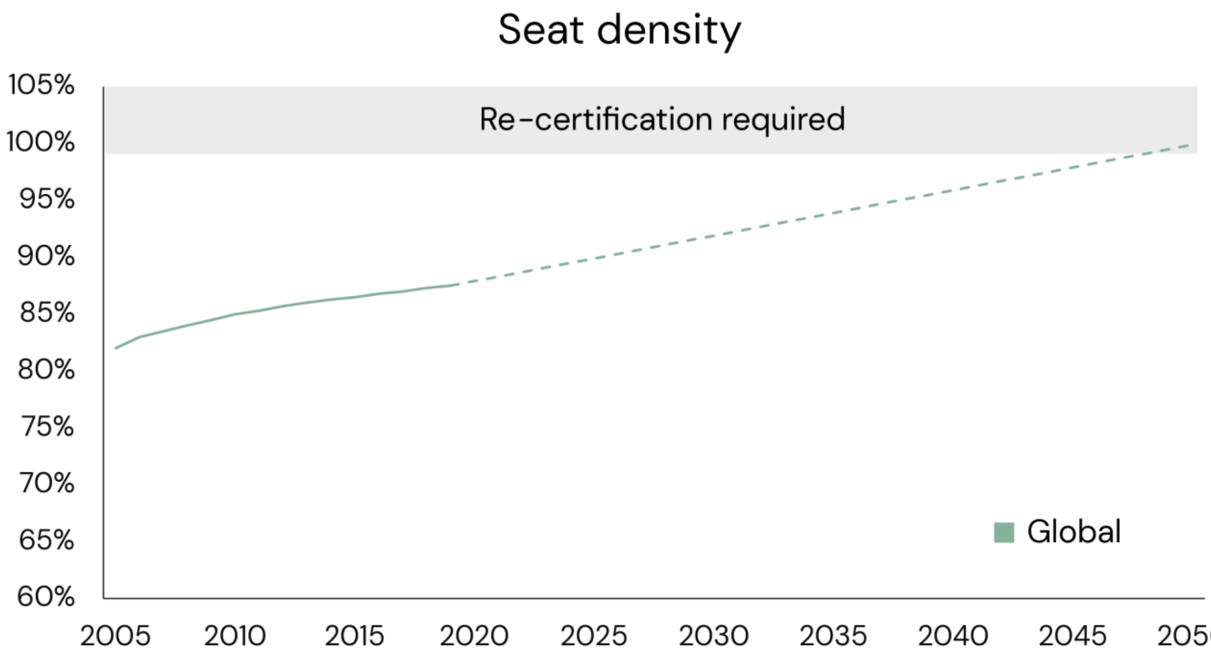


The chart above presents the load factor trends and projections for both the UK and global markets from 2005 to 2050, referencing the Department for Transport (DfT) targets. Load factor exhibited a steady increase between 2005 and 2019, with **an average annual rise of 0.5 percentage points, reaching 82% by 2019**[76]. The UK followed a similar trajectory between 2014 and 2019[77]. However, both global and UK aviation experienced a sharp decline in load factors during the COVID-19 pandemic, with recovery to pre-pandemic levels beginning only in 2023. It is noticed that the UK experienced a bigger hit in load factors. Key reasons for the sharper decline in the UK likely include: (i) more stringent COVID-related travel restrictions in the case of the UK, and (ii) the heavy reliance of the UK aviation on international travel, which was more affected by COVID restrictions [78]

In the Jet Zero Modelling Framework published in 2022[79], the DfT set a load factor cap at 95%. Assuming the historical trend of linear incremental increases in load factor continues, **projections indicate that load factors will reach their capped levels around 2050**, depending on the industry's ability to drive further efficiency improvements.

9.2.2 Seat Density

Figure 21: Seat Density



The chart above illustrates the historical trend and future projections of seat density in global markets from 2005 to 2050. Similar to load factor, seat density experienced a steady increase between 2005 and 2019, rising by approximately **0.4 percentage points annually** reaching **88% by 2019**[80]. This growth has been largely driven by the increasing market share of **low-cost carriers (LCCs)**, which prioritize high seat density to maximize efficiency and profitability.

Based on historical trends, seat density is projected to reach **95% by the mid-2030s**, with a potential increase to **100% by 2050**. Seat density values approaching or exceeding 100% suggest that airlines are reaching the upper limit of the aircraft's certified seating capacity. Operating above this threshold would require regulatory re-certification before such configurations could be legally implemented.

References

[76] *Commercial airlines: passenger load factor worldwide 2024*. en. URL: https://www.statista.com/statistics/658830/passenger-load-factor-of-commercial-airlines-worldwide/ (visited on 02/04/2025).

[77] *Latest quarterly statistics | Civil Aviation Authority*. URL: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/latest-quarterly-statistics/ (visited on 02/04/2025).

[78] House of Commons Committee. *UK aviation: reform for take-off*. Tech. rep. House of Commons Committee, 2022. URL: https://publications.parliament.uk/pa/cm5802/cmselect/cmtrans/683/report.html.

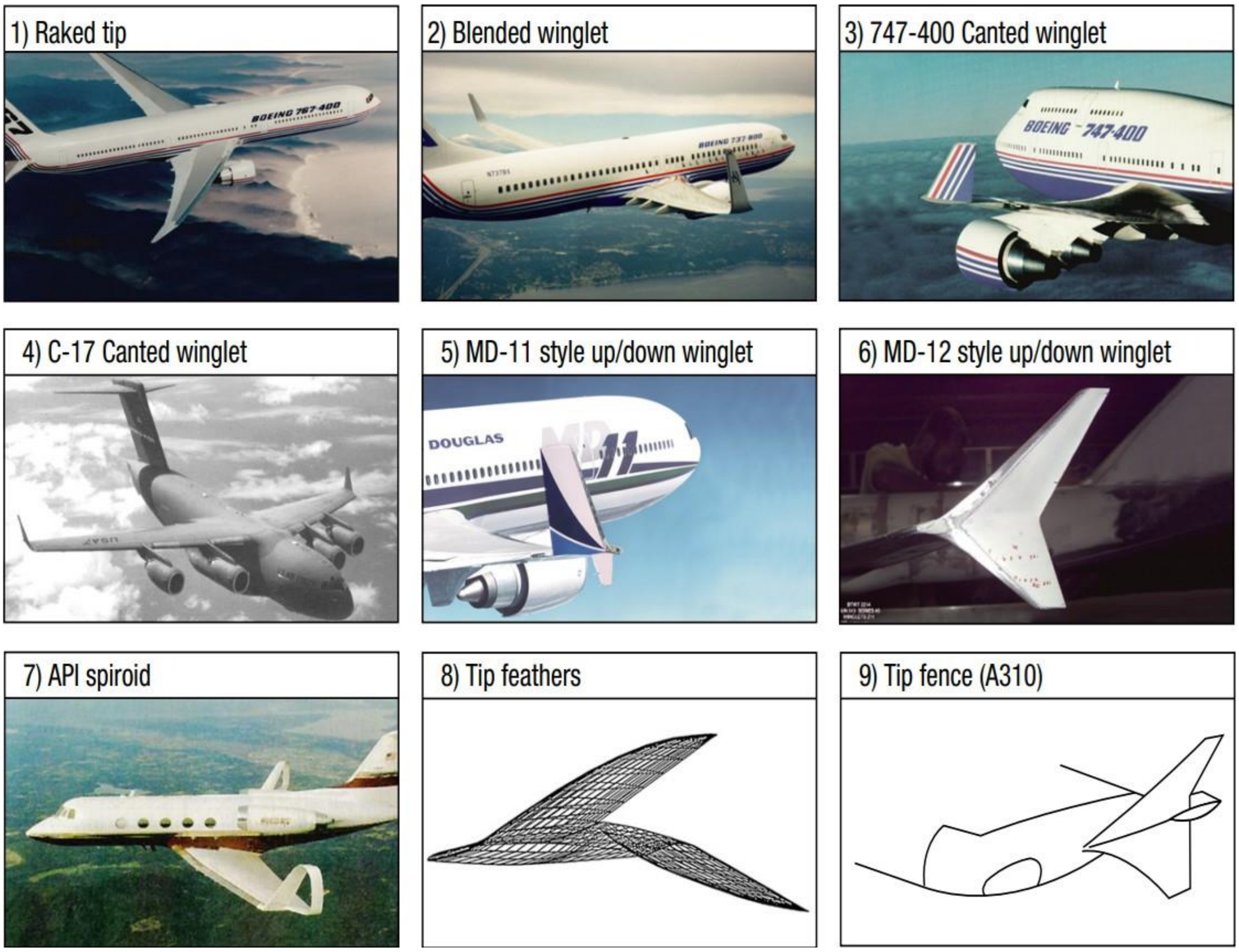
[79] Department of Transport. *Jet zero: modelling framework*. en. Tech. rep. Department of Transport, 2022. URL: https://assets.publishing.service.gov.uk/media/62384b518fa8f540f3202bd4/jet-zero-modelling-framework.pdf.

[80] *Fuel efficiency: Why airlines need to switch to more ambitious measures*. URL: https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/fuel-efficiency-why-airlines-need-to-switch-to-more-ambitious-measures (visited on 02/04/2025).

9.3 Wingtip Devices

9.3.1 Introduction

Wingtip devices are a class of aerodynamic modification used to alter an aircraft's performance or handling characteristics. The term "winglet" is often used, but there is a wide range of tip device types.



A (non-exhaustive) assortment of wingtip device configurations[81]

This briefing note is focused on retrofitting existing aircraft with new tip devices with the objective of increasing the aircraft's cruise lift to drag ratio to reduce fuel burn.

The net performance effects of the wingtip device, as relating to fuel burn, are:

- Increased parasitic drag due to increased wetted area (increased fuel burn).
- Increased aircraft operating empty mass (increased fuel burn).
- Reduced induced drag (reduced fuel burn). See Formation Flight for an explanation of induced drag.

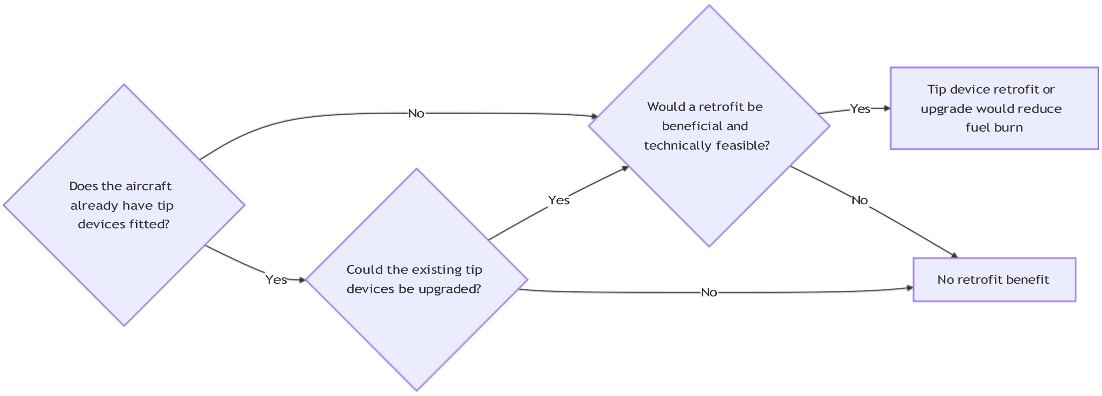
It is entirely possible that the performance benefit from reduced induced drag is overcome by the effects of increased parasitic drag and increased aircraft mass, particularly with older tip device designs. As tip devices reduce fuel burn by reduction of induced drag, they are most effective on flights where the aircraft is heavier. Even when tip devices are beneficial, they are not always included in the original design. For example, blended winglets were introduced on the Boeing 737 NG in 2000, 2 years after production started. In 2014, a higher performance "split scimitar" winglet design was introduced, with retrofit available for all aircraft.

A wingtip device should *not* be thought of as a simple bolt-on appendage. The type of wingtip, and its detailed aerodynamic and structural design, are highly dependent on the design particulars and expected operating conditions of the original wing. In general, greater drag reduction can be achieved by increasing the wingspan, rather than adding tip devices (for equal span increase and tip device height). However a tip device can provide a benefit when the span is limited (for example to fit an ICAO aerodrome reference code limit), or the wing has other structural limits (such as bending capacity). Some modern aircraft are designed without prominent tip devices and their wing designs do not stand to benefit from a "retrofit" of another tip device type at all, for example the Boeing 777 and 787, which have raked wingtips. As such, it is not possible to provide a general, type-independent estimate of the benefit of retrofitting wingtips. Instead, this briefing note will assess the magnitude of the potential benefit of tip device retrofit by examining the commercial UK aircraft fleet type-by-type.

9.3.2 Fleet Assessment

A simple flow chart can be used to assess how many existing aircraft would benefit from wingtip device retrofit.

Figure 22- Fleet Assessment



Below is a list of the regional, narrowbody and widebody aircraft families in the UK fleet[65], and their tip device retrofit status. The entry into service (EIS) and tip device introduction (or retrofit program availability) dates are shown where relevant, as the year of wingtip device introduction roughly indicates the proportion of the type built with or without certain tip devices. The column "Of which suitable for retrofit" excludes aircraft which have already had tip devices retrofitted, because any fuel burn reduction for these aircraft is already included in the baseline case. This value is a loose estimate based on announcements of retrofit programs by major UK operators of each type. As the announcements are usually only made at the start of a retrofit program, it is difficult to know how many aircraft have been retrofitted today.

Family	Wingtip Devices	Number of aircraft in UK fleet	Of which suitable for retrofit
Airbus A320ceo	Split fences as standard on EIS (1988). Sharklets available from new from 2012, retrofit available from 2015[82].	242	60
Airbus A320neo	Standard on all aircraft.	127	0
Airbus A330ceo	Standard on all aircraft.	17	0
Airbus A330neo	Standard on all aircraft.	6	0
Airbus A340	Standard on all aircraft.	5	0
Airbus A350	Standard on all aircraft, but upgraded in 2018 (EIS 2015) [83]. No retrofit upgrade.	30	0
Airbus A380	Standard on all aircraft.	12	0
ATR ATR42	Not included by manufacturer, no retrofit program.	6	0
ATR ATR72	Not included by manufacturer, no retrofit program.	36	0
Boeing 737 Classic	Not included by manufacturer, retrofit available from 2003 (EIS 1984).	17	9
Boeing 737 MAX	Standard on all aircraft.	22	0

Family	Wingtip Devices	Number of aircraft in UK fleet	Of which suitable for retrofit
Boeing 737 NG	Entered service without wingtip devices (1997). Blended winglet available from 2002, split scimitar available (including retrofit) from 2014[84].	147	50
Boeing 757	Not included by manufacturer (EIS 1983), retrofit available from 2005.	11	6
Boeing 777 Gen1	Not included by manufacturer, no retrofit program.	43	0
Boeing 777 Gen2	Standard on all aircraft.	16	0
Boeing 787	Standard on all aircraft.	75	0
Embraer E-Jet	Standard on all aircraft. Upgraded design for E175 only from 2014 (EIS 2004)[85], no retrofit upgrade.	24	0
Embraer EMB100	Original EIS 1995 with no devices but standard on ERJ-145XR (EIS 2002), with retrofit program for others[86].	18	9
BAE Jet-stream 4100	Not included by manufacturer, no retrofit program.	9	0
Total	-	**863**	**134 (15.5%)**

9.3.3 Conclusion

Of the UK aircraft fleet, around 16% could be retrofitted with new or upgraded wingtip devices. The biggest proportion of these are upgrading 737 NG blended winglets to split scimitar winglets, with a fleet fuel saving of 1.8%[87], and upgrading A320ceo winglets to sharklets, for a fuel saving up to 3.5%[88]. Based on the weighted sum of the benefit per aircraft and each type's share of the fleet, the fleet benefit of these changes is estimated at no more than 0.4%. This is an upper bound, as operators tend to deploy older aircraft without modern tip devices on their shorter routes, where the impact of not having the best tip devices is lower.

Note:

The retrofitting efforts by non-UK carriers operating in the UK seem to align with global aviation trends in a bid to improve fuel efficiency. Ryanair, for example, is installing winglets on over 400 of its Boeing 737-800 aircraft [89]. Qantas is similarly updating a quarter of its Boeing 737-800 fleet with split scimitar winglets [90]. This highlights that there is a broader industry push for this measure outside of the UK as well.

Due to the limited impact of wingtip device retrofit, and great uncertainty in the number of suitable aircraft and benefit per aircraft, this has been excluded from the model. Note also that this wingtip device retrofit would not be consistent with other measures in that it effectively represents an opportunity to improve the performance of older aircraft only - more modern aircraft are unlikely to see the same sort of benefits of retrofit due to highly optimized wing and tip device design as built. Therefore, as the older aircraft with retrofitted wingtips are retired and replaced, the effectiveness of the measure would diminish - unlike other measures, it does not represent a systems level inefficiency that would be permanently eliminated.

References

[65] *UK airline data November 2024 | Civil Aviation Authority*. URL: https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airlines/uk-airline-data/uk-airline-data-2024/november-2024/ (visited on 01/30/2025).

[81] Doug McLean. “Wingtip Devices: What They Do and How They Do It”. en. In: *2005 Performance and Flight Operations Engineering*. 2005. URL: https://mentourpilot.com/wp-content/uploads/2020/10/Wingtip_Devices-Doug-McLean-Boeing-flight-safety-conference-2005.pdf.

[82] *Airbus launches Sharklet retrofit for in-service A320 Family aircraft | Airbus*. 2013. URL: https://www.airbus.com/en/newsroom/press-releases/2013-10-airbus-launches-sharklet-retrofit-for-in-service-a320-family (visited on 02/13/2025).

[83] *New pictures of the changed Sharklets for A350 - Leeham News and Analysis*. URL: https://leehamnews.com/2017/11/01/new-pictures-changed-sharklets-a350/ (visited on 02/13/2025).

[84] *Boeing 737 Winglets*. URL: http://www.b737.org.uk/winglets.htm (visited on 02/18/2025).

[85] *The Embraer 175's Enhanced Winglets: How They Save Fuel*. URL: https://simpleflying.com/embraer-175-enhanced-winglets-guide/ (visited on 02/13/2025).

[86] *Embraer to offer retrofit XR winglets on baseline models | News | Flight Global*. URL: https://www.flightglobal.com/embraer-to-offer-retrofit-xr-winglets-on-baseline-models-/37294.article (visited on 02/13/2025).

[87] *Sustainability*. URL: https://www.jet2plc.com/sustainability (visited on 02/18/2025).

[88] *Dubai 09: A320's sharklets to deliver 3.5% lower fuel burn from 2012 | News | Flight Global*. URL: https://www.flightglobal.com/dubai-09-a320s-sharklets-to-deliver-35-lower-fuel-burn-from-2012/90332.article (visited on 02/18/2025).

[89] Ryanair. *RYANAIR CUTS CARBON EMISSIONS BY 165,000 TONNES WITH WINGLET RETROFIT*. en-US. Jan. 2023. URL: https://corporate.ryanair.com/news/ryanair-cuts-carbon-emissions-by-165000-tonnes-with-winglet-retrofit/ (visited on 03/14/2025).

[90] Channing Reid. *Qantas To Boost Fuel Efficiency With Split Scimitar Boeing 737 Wingtips*. en. Section: Airline News. Feb. 2024. URL: https://simpleflying.com/qantas-boeing-737-800-wingtip-installation/ (visited on 03/14/2025).

Version

FINAL