ICAO

INTERNATIONAL CIVIL AVIATION ORGANIZATION

REPORT ON THE FEASIBILITY OF A LONG-TERM ASPIRATIONAL GOAL (LTAG) FOR INTERNATIONAL CIVIL AVIATION CO_2 EMISSION REDUCTIONS

Appendix M3 Technology Sub Group Report

ICAO COMMITTEE ON AVIATION ENVIRONMENTAL PROTECTION
MARCH/2022

APPENDIX M3

LTAG-TG TECHNOLOGY SUB GROUP REPORT

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LIST OF ACRONYMS

3D	Three Dimensional
A	Maximum Diameter
ACA	Advanced Concept Aircraft
ACES	Advanced Concepts and Energy Storage
ADP	Aerodynamic Design Point
AFC	Active Flow Control
ANOPP	Aircraft Noise Prediction Program
App	Approach Noise
AR	Aspect Ratio
ASDL	Aerospace Systems Design Laboratory
ATK	Available Tonne Kilometer
ATW	Advanced Tube and Wing
BJ	Business Jet
BLI	Boundary Layer Ingestion
BPR	Bypass Ratio
BWB	Blended Wing Body
CAEP	Committee on Aviation Environmental Protection
C_D	Drag Coefficient
CFD	Computational Fluid Dynamics
CLEEN	Continuous Lower Energy, Emissions, and Noise
CL	Lift Coefficient
CLmax	Maximum Lift Coefficient
CMC	Ceramic Matrix Composites
CMO	Current Market Outlook
CMPGEN	Compressor Map Generation Tool
CO_2	Carbon Dioxide
CO_2 MV	CO_2 Metric Value
CTE	Critical Technology Elements
DF	Fuselage Height
DHC	De Havilland Aircraft of Canada
DoE	Design of Experiments
DP	Distributed Propulsion
EAP	Electrified Aircraft Propulsion
EDS	Environmental Design Space
ECS	Environmental Control System
EI	Energy Intensity
EIS	Entry into Service
ERA	Environmentally Responsible Aviation
F_n	Maximum SLS Thrust (Installed)
FAA	Federal Aviation Administration
FB/ATK	Fuel burn per Available Tonne Kilometre
FESG	Forecasting and Economics Support Group
FLOPS	Flight Optimization Program
Flt ENv	Flight Envelope
FPR	Fan Pressure Ratio
GE	General Electric
GT	Georgia Institute of Technology

GTF	Geared Turbo Fan
HLFC	Hybrid Laminar Flow Control
HPT	High Pressure Turbine
HT	Horizontal Tail
HWB	Hybrid Wing Body
ICA	Initial Cruise Altitude
ICAO	International Civil Aviation Organization
ICCAIA	International Coordinating Council of Aerospace Industries Associations
IE	Independent Expert
IEIR	Independent Expert Integrated Review
IS	Integrated Scenario
K	Degrees Kelvin
L/D	Lift-to-Drag Ratio
LdgFL	Landing Field Length
LPT	Low Pressure Turbine
LTAG	Long-Term Aspirational Goal
LTO	Landing and Take-off Cycle
M&S	Modeling and Simulation
M_{des}	Design Cruise Mach number
MCR	Maximum Cruise
MDG	Modeling and Database Group
MDP	Multiple Design Point
MDAO	Multidisciplinary Analysis and Optimization
MDO	Multidisciplinary Optimization
MEW	Manufacturer’s Empty Weight
MJ	Mega Joule
MLM	Maximum Landing Mass
MT	Mid-Term
MTF	Mixed Flow Turbofan
MTOM	Maximum Take-off Mass
NASA	National Aeronautics and Space Administration
NB	Narrow Body
ND	Nutating Disc
NLF	Natural Laminar Flow
NPSS	Numerical Propulsion System Simulation
OEM	Original Equipment Manufacturer
OEW	Operating Empty Weight
OPR	Overall Pressure Ratio
P3	Compressor Exit Pressure
pax	Number of Passengers
P&W	Pratt & Whitney
PDE	Pulse Detonation Engines
R_1	Range at Maximum Take-off Mass and payload
R_2	Range at Maximum Take-off Mass and fuel
R&D	Research and Development
RGF	Reference Geometric Factor
RJ	Regional Jet
RPK	Revenue Passenger Kilometre
SAF	Sustainable Aviation Fuels

SDSG	Scenarios Development Sub Group
SFC	Specific Fuel Consumption
SG	Sub Group
SLS	Sea Level Static
SME	Subject Matter Expert
SUGAR	Subsonic Ultra Green Aircraft Research
SW	Wing Area
SWR	Wing Loading
T_3	Compressor Rotor Exit Temperature
T_{40}	Combustor Exit Temperature
T_{41}	Turbine Rotor Inlet Temperature
TA	Twin Aisle (twin-engine) aircraft (>210 seats)
Tahg	Technology Ad Hoc Group
TG	Task Group
TIT	Turbine Inlet Temperature
TOC	Top of Climb
TOFL	Take-off Field Length
TRA	Technology Reference Aircraft
TRL	Technology Readiness Level
TTBW	Transonic Truss-Braced Wing
TWR	Thrust to Weight Ratio
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UDF	Unducted Fan
VT	Vertical Tail
WATE++	Weight Analysis of Turbine Engines
WB	Wide Body
WF	Fuselage Width
WG1	CAEP Working Group One (Noise -Technical)
WG3	CAEP Working Group Three (Emissions -Technical)
XL	Fuselage Length

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APPENDIX M3.1. EXECUTIVE SUMMARY

1.1 INTRODUCTION

CAEP organized the Technology Sub-group (Tech SG) within the Long-Term Aspirational Goals (LTAG) task group to better understand future evolutionary technologies for airframes, propulsion systems, and advanced concepts (including energy storage) up to 2050. The intent of these aviation technologies and advanced concepts is to reduce CO_2 emissions in an effort to mitigate aviation's carbon footprint. The Technology Sub-group has 102 members nominated by CAEP Member States and Observers. The Tech SG is led by Dimitri Mavris, nominated by the United States, and by Wendy Bailey, nominated by Canada. Dimitri Mavris is the Director of Aerospace Systems Design Laboratory at the School of Aerospace Engineering at the Georgia Institute of Technology. Wendy Bailey is the Chief of Environmental Protection and Standards in Civil Aviation at Transport Canada and is Canada's CAEP Member.

The Tech SG members are divided into five ad hoc groups relevant to their expertise including the Airframe Ad Hoc Group, the Propulsion Ad Hoc Group, the Advanced Concepts and Energy Storage (ACES) Ad Hoc Group, the Vehicle Impact Assessment (VIA) Ad Hoc Group, and the Modeling and Simulation (M&S) Ad Hoc Group.

Collaboration both within the Tech SG Tahgs and the broader LTAG-TG, in addition to other CAEP Working Groups, including WG3, MDG, FESG, FTG, and ISG was critical to this effort. As the Tech SG was tasked with providing MDG, FESG, and SDSG with the data input they required to make their future projections, significant collaboration efforts were also made to better understand these needs and fulfill their requirements in a productive and cohesive manner.

The Tech SG methodology for assessing CO_2 reduction potentials in 2050 is based on the Independent Expert Integrated Review (2019 IEIR) Report [1]. The main distinction for LTAG from the IEIR methodology was a singular focus on CO_2 reduction potential, instead of interdependencies between noise, emissions, and CO_2. From a high-level perspective, the LTAG methodology involved four main steps including creating the technology reference aircraft (TRA), assessment of advanced tube and wing (ATW) configurations, assessment of advanced concept aircraft (ACA), and generation of the necessary information for the fleet-wide modeling and cost assessment.

The Tech SG used the four conventional 2019-IEIR TRAs for a Business Jet, Regional Jet, Single-Aisle and Twin-Aisle Aircraft as a starting point for the analysis and adding a notional turboprop aircraft as a fifth TRA, to serve as a foundation for study of alternative energy sources that may become available. The objective of the Tahgs was to determine the additional benefits above and beyond the IEIR projections for 2037 to a 2050 timeframe for each of the TRAs. The Tahgs also had to determine the level of improvements expected for ATW configurations. For each TRA class, a three-point estimate for each airframe and propulsion technology area was provided to the M&S Tahg, which were defined as higher progress (most aggressive technology level), medium progress (nominal technology level), and lower progress (lowest technology level). The Tahgs collectively agreed that the primary starting point for the ATW and ACA projections to 2050 was the 2019 IEIR report. While the ATW assessment was quantitatively based, the ACA modelling approach for future concepts was agreed to be qualitative and relied on previous high-quality published studies to establish the improvement above and beyond future ATWs.

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[1] "Independent Expert Integrated Technology Goals Assessment and Review for Engines and Aircraft", ICAO Doc 10127, 2019. https://www.icao.int/environmental-protection/Pages/ClimateChange_TechGoals.aspx

In summary, the Technology Subgroup has completed its task by conducting an extensive and intensive review of potential technological improvements available to aircraft (airframes and propulsion), relating to the reduction of CO_2 emissions over the next few decades. In considering technological advances, both evolutionary and revolutionary, for five TRAs, it was found that reductions of CO_2 emissions may be feasible in the ranges of approximately 30 to 40% in 2050, relative to the 2019 reference.

All aircraft follow similar improvement trends. However, the potential improvements are lower for the smaller aircraft classes (turboprops, business jets and regional jets) compared to the larger aircraft classes (narrow body and wide body). This is due to the lower potential benefits achievable via technology infusions, and to the shorter mission ranges that limit the ability for greater fuel burn reduction.

With respect to advanced concept aircraft (ACA), these were considered to be possible by 2035 and onward. Most near-term applications are for smaller aircraft. Larger aircraft will take more time to develop but will have a greater impact on carbon reduction. ACA alternate airframes may yield a 10-15% energy intensity reduction compared to the same year ATWs. ACA propulsion with or without alternative energy could happen by 2035. Energy intensity reductions between 10 to 15% compared to the same year ATWs is possible. It is important to note that alternative energy solutions are highly dependent on the availability of energy infrastructure. Both electrified aircraft propulsion and hydrogen-fueled aircraft are examples of evolutionary and revolutionary technologies that can contribute to CO_2 reductions. However, the carbon reduction possible from electrification is highly dependent on the carbon intensity if the local electrical grid, while the carbon reductions from hydrogen will be highly dependent on the carbon intensity of production method used for the hydrogen.

Change is possible by 2035, but there is no time to waste. ACAs will require large scale demonstrations. In the case of non-drop-in energy, substantial change to the energy infrastructure available to aviation in required. Business models may have to change to adapt to low carbon aircraft range capabilities. Substantial investment will be required.

The structure of the appendix is to introduce the Tech Sub Group and the reference aircraft utilized in the study. Next, the technology bucket impacts to those reference airframes are provided based on the Technology ad hoc group input. Subsequently, the results of the ATW are presented and the rationalization of the ACAs in the out years is provide. And finally, the data necessary by LTAG to complete the study is discussed. A high-level overview of each step is provided here.

1.2 TECHNOLOGY REFERENCE AIRCRAFT

The Tech SG chose the same generic aircraft categories used by MDG/FESG [2] in its forecast and fleet evolution analysis which are defined by seat capacities [3] from business jet up to wide body:

Business Jet (BJ)	≤20 seats
Turboprop (TP)	20-85 seats
Regional Jet (RJ)	20-100 seats
Narrow Body (NB)	101-210 seats
Wide Body (WB)	> 210 seats

These categories represent the major classes of vehicles in service in 2018. The initial plan was to use generic aircraft in each vehicle class to avoid competition within the group, but it became clear that problems with availability and consistency of input data, and to allow for validation of the baselines by International Coordinating Council of Aerospace Industries Associations (ICCAIA) made it more practical

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[2] MDG is the Modeling Design Group and FESG is the Forecasting and Economics Support Group
[3] CAEP/11-FESG-MDG/7-IP/09

to employ a specific aircraft fitting into each class as notional references. This also allowed for participating organizations to provide additional data points for the reference aircraft. The reference aircraft selected, with guidance from ICCAIA, were:

BJ	Notional G650ER
TP	Notional DHC Dash 8-400
RJ	Notional E190E2
NB	Notional A320neo
WB	Notional A350-900

1.3 WB NOTIONAL A350-900MODELING APPROACH

The Tech SG required a M&S framework to assess the impacts of the technologies for the three-time frames. The Aerospace Systems Design Laboratory in the Georgia Institute of Technology (GT/ASDL) was chosen to assist with this task employing their integrated aircraft modeling and simulation environment known as the Environmental Design Space (EDS) [4]. EDS can predict the fuel burn, NO_x emissions, and noise metrics in a single framework. The EDS modeling environment incorporates modules developed by NASA for airframe and propulsion system modeling and includes four main phases of execution including, initialization, vehicle design, vehicle performance evaluation, and data output. EDS uses a simultaneous, multi-design point method to generate the engine cycle, which means EDS converges on five design points simultaneously including ADP (Aero Design Point), TOC (Top of Climb), TKO (Take Off), SLS Installed Thrust, and SLS Uninstalled Thrust. It also incorporates physical performance constraints in both the engine and airframe analyses to ensure the resulting model is a feasible design.

1.3.1 Technology Reference Aircraft

The technology reference aircraft (TRA) simulated within EDS are based on public-domain available data and are representative of the five notional aircraft chosen by the Tech SG. These models were verified in an iterative manner based on feedback from ICCAIA. This process yielded five TRAs upon which the technology area impacts could be applied to a given aircraft for 2030, 2040, and 2050. The calibration process involved two stages, first calibrating the engine model and then the airframe model. Publicly available manufacturer data, where available, took precedence over other sources because of its greater accuracy. Since CO_2 metric data is yet to be made publicly available, the calibration process utilized fuel burn as a proxy matching parameter. Fuel burn has the added benefit of being a logical efficiency metric for given vehicle settings and mission performance parameters that can be derived from payload-range data published by manufacturers. The values used for the baseline TRAs with respect to payload, range, passenger counts, cruise Mach number, and cruise altitude for each of the five vehicle categories are all detailed in this report.

1.3.2 Advanced Tube and Wing

After baselining the TRAs, the ATWs are modeled for each time frame. In the first phase a notional TRA is chosen based on passenger class and is used as baseline for comparison to assess aircraft performance in the 2030, 2040, and 2050-time frames. In the second phase of the ATW assessment process, the aircraft model calibration is performed in EDS. Once the TRA models are calibrated, the future technology impacts are applied to these baseline ATW vehicles. As mentioned earlier, the LTAG modeling

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[4] Kirby, M. and Mavris, D., "The Environmental Design Space," 26th International Congress of the Aeronautical Sciences, Anchorage, Alaska, 14 - 19 September 2008.

only considered fuel burn as the proxy for the long-term aspiration goal of reducing CO_2. This leads to the third phase of the ATW assessment process where technology impacts are identified in four categories from their respective Tahgs: propulsion technology impacts, system technology impacts, structures/materials technology impacts, and aerodynamic technology impacts.

For each technology considered, technology impacts are identified for the 2030, 2040, and 2050 timeframes. In each of the three timeframes, lower progress, medium progress, and higher progress confidence levels are identified for the technology baskets in the future. In the fourth phase the technology impacts are implemented into EDS using a Design of Experiments (DoE) methodology to create surrogate models that allow rapid exploration of the design space. The final selected designs for each time frame have the minimum fuel burn at the Range at Maximum Take-off Mass and payload (R_1) point compared to the optimized 2018 TRA.

In the fifth phase the vehicle level benefits are quantified. The optimized vehicle results are determined at the R_1 range but the final results sent to MDG are quantified at the aircraft design range. The results include Maximum Take-off Mass (MTOM) and FB/ATK projections in the 2030/2040/2050 timeframes at the lower, medium, and higher technology progress levels. The sixth phase of the ATW assessment process projects the vehicle level results to future technology and vehicle scenarios to assess fleet penetration in 2030/2040/2050. There are three technology scenarios and each contains low, medium, and high progress level projections. They all incorporate per annum energy intensity change relative to the previous decade. The fleet penetration will be governed by a market split between ATW and ACA vehicles as well as future demand scenarios and production rate considerations. The last step is to approximate cost estimation and investment requirements for technology maturation and introduction. The costs associated with the ATWs were determined in coordination with the Cost Estimation ad hoc group.

1.3.3 Advanced Concept Aircraft

The Advanced Concept Aircraft (ACAs) were not modeled quantitatively as with the ATWs. This was a logical choice due to several factors including time and resource constraints, and the inherent uncertainties related to ACA development which did not justify the use of overly precise models. A different methodology was needed than the ATW assessment approach. The methodology used by the Tech SG was more qualitative in nature and involved the following steps: (a) Configuration/ architecture screening based on potential benefits per scenario, (b) Technical and non-technical barrier identification, (c) Assessment of advanced aircraft concepts through scorecards, (d) Identification of representative aircraft for each class, (e) Vehicle level benefit quantification (compared to same-year ATW), (f) Technology and vehicle scenario-based projection (fleet penetration), and (g) Cost estimation and investment quantification.

The ACA methodology begins with a wide search of all the aircraft concepts found in literature search using authoritative published reports, ICAO Stocktaking, and LTAG-TG member input. Then, these concepts are mapped against the three technology scenarios, T1 – Advanced tube-and-wing, T2 – Advanced concept aircraft, drop-in-fuels, and T3 – Advanced concept aircraft, non-drop-in fuels and energies. Each configuration is qualitatively evaluated based on its potential benefit which is then used to formulate a subset of configurations that proceed to the next phase of the assessment process. The next step is to identify the technical and non-technical barriers of each representative aircraft configuration that is selected previously. In the third step of the process, scorecards are used to assess a range of ACAs side-by-side. The scorecard allows collection of Subject Matter Experts' (SMEs) perspectives on the readiness, attainability, and potential benefits of each aircraft concept for each technology scenario. Then, using the readiness and attainability evaluations of the concepts collected through scorecards, two overlapping ACA "baskets" of innovation are identified beyond the ATW, with conventional or drop-in fuel: ACA T2 is representative of alternative architecture airframes and/or propulsion (with conventional or drop-in fuels), and ACA T3 is representative of advanced airframes and advanced propulsion characterized by the use of non-drop-in fuels and energies, mainly hydrogen or battery electric. Each group of aircraft were characterized as a whole, which is advanced to the next step of this methodology. This helps to avoid implying any single concept is a winner over others by characterizing the potential benefits representative of a group of relevant concepts rather than just one.

The MDG fleet analysis requires vehicle level benefits which are quantified by referencing authoritative studies previously performed by/for R&D organizations. The ACES Tahg isolated the benefits and challenges associated with making a step change to an alternative architecture beyond an ATW by studying equivalent technology advanced conventional architecture configurations. For each vehicle class, a range of energy intensity changes (change in energy consumption per unit of transport (MJ/ATK)) representing low to moderate and high progress relative to the same year ATW was estimated. Then MDG would need the identification of proxy aircraft within each aircraft category to represent the basis of change of the ACA energy intensities. The figures of merit for each ACA class were in terms of MJ/ATK to capture the energy intensity independent of the type of fuel used. To obtain the impact on CO_2 emissions, this energy metric is then combined with the lifecycle emissions factor provided by the Fuels SG. Finally, aircraft market share projections of ACAs vs ATWs are made for 2018-2070, with an extra 20 years of fleet assessment included to realize potential reductions from the new technologies introduced in 2050.

1.4 AVIATION FUEL BURN AND CO_2 REDUCTION

Many future aviation technologies are linked to fuel burn improvements which directly link to aircraft CO_2 emissions-reduction potential. Large-scale national and international research programs with cooperation between industry, government and academia continue to be key enablers to advance and mature the state of art in breakthrough integrated technologies. These technologies can be broadly categorized as improvements in the areas of aerodynamics, structures and materials, systems, or propulsion. In addition, significant MDAO benefits are feasible via constraint relaxation of wing aspect ratio enabled by structural/materials improvements and advanced load alleviation.

In aerodynamics, the Tech SG considered technologies in the areas of lift dependent or induced drag reduction technologies like increasing wing span and aspect ratio and modified winglets. Viscous drag reduction technologies like laminar flow and/or conditioned turbulent boundary-layer flow, micro-scale ‘riblet’ geometries, Hybrid Laminar Flow Control (HLFC), were also included. Within aerodynamics are also integration and simulation technologies that represent improvements in CFD and modeling that have enabled developments like Active Flow Control (AFC).

For structures and materials technologies, the Tech SG incorporated impacts from lightweight technologies such as composites and advanced metals, multifunctional optimized design, shape control in terms of active or passive alleviation, and nacelle improvements with new designs and components for weight savings.

The Tech SG recognizes the importance of benefits obtained from systems integration in aircraft design. This includes hybrid and more electric aircraft as well. Engine power extraction is one area that is currently undergoing technology improvement where SFC gains can be made from replacing hydraulic and pneumatic systems with electric counterparts. Cabin environmental control can be done with adaptive ECS (Environmental Control System) that also improves SFC.

In the area of propulsion there are a number of technologies that can reduce future aircraft’s CO_2 emissions. The Propulsion Tahg agreed that the propulsion impacts from the 2019 IEIR study would be used as an initial set of values and updates were made based upon recent developments informed by ICCAIA. The propulsion technology impacts forecasted improvements in the 2030, 2040 and 2050-timeframes for each vehicle class for improvements in thermal efficiency (represented by overall pressure ratio and small core efficiency improvement parameters), propulsive efficiency (represented by the fan pressure ratio parameter), and weight reduction (represented by propulsor and core component weight reduction relative to TRA)

As a result of the Tahg efforts, a series of ATW technology baskets were established for each vehicle class and time frame of 2030, 2040, and 2050. At each out year, a high, medium, and low progress level of improvements were defined to apply the TRAs to obtain the ATWs, which are provided in Annex D.

1.5 PRINCIPAL RESULTS

1.5.1 ATW Findings

The vehicle-modelling approach utilized in the 2019-IEIR study relied on the Georgia Institute of Technology modeling capabilities for conventional aircraft and was applied for the five TRAs to establish the ATW configurations for 2030, 2040, and 2050. The relevant Tahgs provided guidance for design constraints and ranges for each class of ATW in each time frame.

The ATW assessment methodology yielded results for Maximum Take-off Mass (MTOM), Fuel burn per Available Tonne Kilometre (FB/ATK), % FB/ATK relative to 2018 TRA, FB/ATK per annum improvement relative to 2018 TRA, and FB/ATK per annum relative to the previous decade. This data was calculated for all three-time frames that were studied, 2030, 2040, and 2050, for each of the five vehicle classes. Within each timeframe, calculations are made and documented at lower, medium, and higher progress levels. The results of each vehicle class ATW are organized in a single table that summarizes the calculations across all three-time frames and progress levels. The wide body ATW results table is presented as a representative example in the table below. The remaining vehicle class results are provided in Sec 5.3 of this report.

Table 1-1: WB ATW Results at the Design Range

Timeframe	**Technology Confidence Level**	**MTOM (kg)**	**FB/ATK (kg/ATK)**	**% FB/ATK Rel. 2018 TRA**	**FB/ATK Per Annum (Rel. 2018 TRA)**	**FB/ATK Per Annum (Rel. Previous Decade)**
2018	**TRA**	280,000	0.1979			
2030	**Lower Progress**	276,585	0.1905	-3.73%	-0.32%	-0.32%
	Medium Progress	267,442	0.1794	-9.35%	-0.81%	-0.81%
	Higher Progress	253,440	0.1648	-16.70%	-1.51%	-1.51%
2040	**Lower Progress**	268,138	0.1694	-14.38%	-0.70%	-1.17%
	Medium Progress	255,106	0.1543	-22.02%	-1.12%	-1.49%
	Higher Progress	240,933	0.1399	-29.30%	-1.56%	-1.63%
2050	**Lower Progress**	260,628	0.1561	-21.11%	-0.74%	-0.82%
	Medium Progress	247,160	0.1429	-27.76%	-1.01%	-0.76%
	Higher Progress	233,211	0.1304	-34.07%	-1.29%	-0.70%

When examining results in these tables across the vehicle classes, the potential percentage improvements are lower for the smaller aircraft classes (TP, BJ, and RJ) than the larger classes (NB and WB). One reason for this is the lower potential benefits achievable via technology infusions identified by the Tahgs, and the shorter mission ranges that limit the ability for greater fuel burn reductions.

The results were also visualized in plots to portray improvements across decades. As a representative example, a plot of the wide body ATW results for %FB/ATK relative to 2018 TRA is depicted in the figure below with all three progress levels indicated. The remaining plots for the other vehicle classes are presented in Sec 5.3 and show similar trends over the decades. All of these ATW projections are based on improvements in aircraft fuel burn efficiency that are represented by the technology impacts provided by the Tahgs. This data is plotted in Figure 5.7 to Figure 5.11 to better illustrate the FB/ATK improvements across decades. This shows the projected improvements in aircraft fuel burn efficiency given the technology impacts provided by the Tahgs and after following the optimization process described in the full document. It is observed how all airframes follow similar improvement trends. However, the potential percentage improvements are lower for the smaller aircraft classes (TP, BJ, and RJ) than the larger classes (NB and WB).

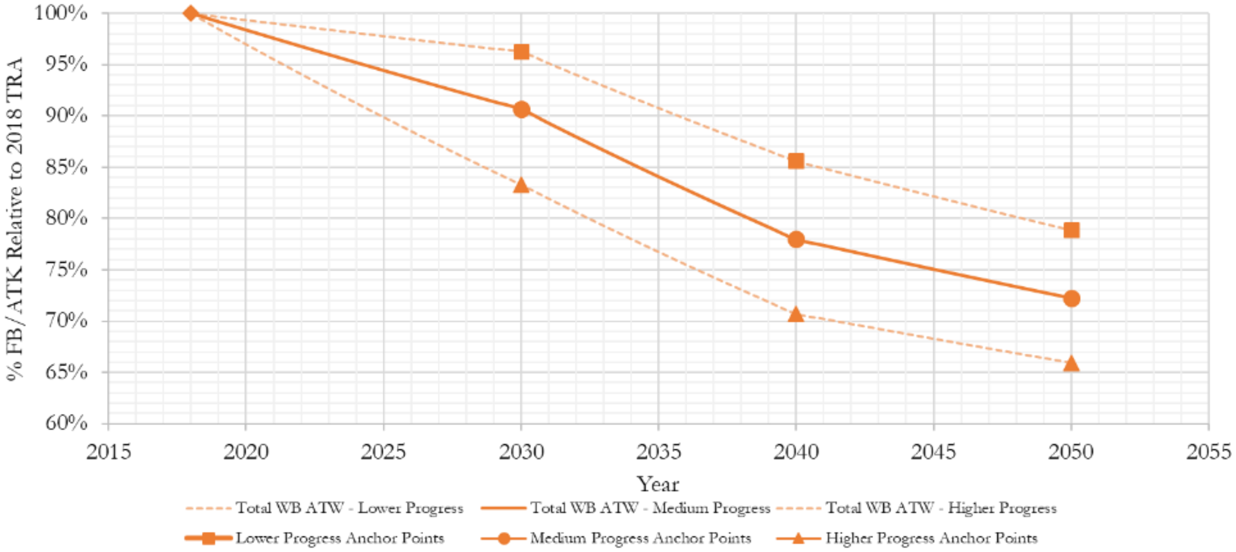


Figure 1-1. WB ATW FB/ATK Improvements Relative to the previous Decade

1.5.2 ACA Findings

While the ATW assessment was quantitatively based, the ACA modelling approach for future concepts was agreed to be qualitative and relied on previous high-quality published studies to establish the improvement above and beyond future ATWs. The ACES Tahg performed the ACA qualitative assessments with a seven-step procedure including identifying barriers for each concept, determining fleet penetration under different technology scenarios, and cost estimation. The ACA assessment methodology was more qualitative in nature and are not based on MDAO design efforts as assembled for the ATWs. The ACA methodology yielded timelines about the earliest potential entry into service (EIS) as well as tables recording energy efficiency for all five vehicle classes based on a qualitative review of reputable documents and studies of numerous concepts. Observations were drawn and representative ACAs were identified for each vehicle class and timeframe as provided below and further discussed in APPENDIX M3.6.

- ACES led the LTAG Tech assessment of ACAs. Existing published material was used to develop consensus on potential timing and estimated benefits for each aircraft category. Care was taken to not suggest specific winning aircraft concepts.
- Change is always hard. Step change is harder. Technical capability and maturity are necessary but not sufficient conditions to implement a configuration step change.
- Major global drivers beyond the aviation sector are active now. The combination of factors sets the stage for an ACA-driven revolution in aviation to help provide further emission reductions.

- Significant ACA-relevant R&D is underway or planned for the next decade, including flight demonstrations. Most near-term application is envisioned first for smaller aircraft, e.g. smaller TP aircraft. Smaller aircraft provide learning opportunities for technologies that scale to larger aircraft (RJ and NB). Larger aircraft will have more impact on carbon reduction but lag in time.
- ACA-relevant airframes are assumed in current study to be possible by 2035. Large-scale, integrated flight demonstration is required. Possible energy intensity reduction due to configuration step change between 5-15% compared to ATWs is assumed.
- ACA-relevant propulsion with or without alternative energy is possible by 2035. Alternative energy solutions are highly dependent of availability of energy infrastructure. Large-scale, integrated flight demonstration is required. Energy intensity reduction between 5-15% compared to ATWs is assumed.
- Electrified aircraft propulsion is coming. Initial benefits will be small but significant and instigate change. Hybrid systems are likely initially to balance weight and range challenges. The carbon reduction from electrification is highly dependent on local grids around the world.
- Hydrogen-fueled aircraft may be achievable technically and reduce in-flight carbon emissions to zero. The non-technical attainability challenges and commercial viability are likely greater challenges to overcome. Aircraft design and mission capability trades will be impacted due to the properties of hydrogen. Energy use may increase to yield a decrease in carbon emissions in flight. The life cycle carbon reduction benefits will be highly dependent on the production method for the hydrogen.
- Change is possible by 2035, but there is no time to waste. ACAs will require large scale demonstrations. In the case of non-drop-in energy, substantial change to the energy infrastructure available to aviation in required. Business models may have to change also adapting to low carbon aircraft range capabilities.

The scenarios envisioned two different levels of innovation beyond the ATWs. The first is ACA T2 which represents alternative architecture airframes and/or propulsion with conventional or drop-in fuels. The second is ACA T3 which represents advanced airframes and advanced propulsion characterized by the use of non-drop-in fuels with or without alternative airframe architecture changes. The descriptors “T2” and “T3” indicate a system of three technology levels or alternatives: T1 including ATWs only, T2 including the addition of ACAs with conventional or drop-in fuels and T3 which includes all advanced aircraft including ACAs with and without non-drop-in fuels. In addition, three integrated scenarios (IS#) were defined for the LTAG analysis. For each scenario, Tech SG provides a summary table for each of the five aircraft classes under consideration. Each summary table includes information on per annum efficiency improvements, range and payload information, and new aircraft market share from 2018-2070.

Based on this review, ACES established the EIS timelines of when the T1, T2, and T3 concepts of each vehicle category were projected to enter the fleet. As a representative example, the wide body EIS timeline is provided in Figure 1-2 below. The timelines for the other vehicle classes are documented in APPENDIX M3.6 of this report. The ACA quantitative results include energy efficiency benefits relative to the corresponding year’s ATW for all five vehicle classes, the wide body example is provided in Table 1-2 and was repeated for each vehicle class as provided in APPENDIX M3.6. This table only shows energy benefits at 2035- and 2050-time frames, because the ACES Tahg believes T2 and T3 concepts for wide body aircraft will not enter the fleet those years. In addition, only T2 concepts are expected in 2035 and wide body T3 concepts are not expected until 2050. The tables indicate the ACES Tahg estimates for energy efficiency improvements at three progress levels, but only for the timelines when T2 and T3 concepts are expected to enter the fleet for a given vehicle class. Other vehicle classes include the 2040-year timeframe. This data would serve as the basis for the necessary calculations for the MDG analysis, described in the subsequent section.

Figure 1-2. Wide Body ACA Identification of Earliest EIS

Table 1-2. Wide Body Energy Efficiency Benefits Relative to the Corresponding Year's ATW

Technology Scenario	Point Estimates	2035 Δ(MJ/ATK)	2050 Δ(MJ/ATK)
T2	Lower Progress	-5%	-5%
	Medium Progress	-10%	-10%
	Higher Progress	-15%	-20%
T3	Lower Progress	-	+40%
	Medium Progress	-	0%
	Higher Progress	-	-10%

1.6 INPUT TO MDG

The Modeling and Database Group (MDG) needs two key inputs from the Tech SG: The fuel demand of the future fleet and mix of aircraft in the future fleet. The fleet-level fuel demand is modeled by Tech SG as the energy intensity in each time frame. These are the predicted trends in energy use per available tonne kilometers (MJ/ATK) for each vehicle class at the technology levels T1, T2, and T3. The energy intensity predictions are also made for each of the lower, medium, and higher progress levels in the future.

The aircraft fleet mix in the future is the predicted combination of ATW-T1, ACA-T2, and ACA-T3 entering the fleet in all the future time frames. This represents the market share for each vehicle concept and technology level and their respective entry into service timelines. The market shares are estimated for all of the vehicle classes and provided to MDG for fleet analysis. The market share mix is rounded off to the nearest 5% by the Forecasting and Economics Support Group (FESG) so it includes at least this level of imprecision. The data tables showing the market split extending out to the 2070, which is beyond the 2050-time frame when the technology level is frozen. This is a logical step in order to give the 2050 technology vehicles enough time to enter the market and have a measurable impact.

The input data sent to MDG is presented in a series of three color-coded tables for each of the five vehicle classes studied by the Tech SG. The orange aircraft represent the ATW-T1s, green aircraft represent the ACA-T2s, and blue aircraft represent the ACA-T3s. The bands around the medium progress line represent the uncertainty between the lower and higher progress scenarios.

The wide body vehicle class energy intensity levels and fleet mix are presented here as a representative example of the input data sent to MDG for all the vehicle classes. The other vehicle classes are summarized in sections APPENDIX M3.6 of this report and detailed in Annex G.

The first table below represents the wide body energy intensity levels relative to the 2018 TRA for ATW-T1 from 2018 to 2070 at the lower, medium, and high progress levels. The next table below represents the wide body energy intensity reductions of the ACA-T2 and ACA-T3 relative to the ATW-T1 from the year they enter service onward, at the lower, medium, and high progress levels. The next table is the last one provided to MDG to summarize the wide body vehicle class market share mix of vehicles entering the fleet across all the time frames from 2018 to 2070 in the three integrated scenarios IS1, IS2, and IS3.

Table 1-3: Wide Body ATW-T1 Energy Intensity at Each Waypoint Normalized to the TRA

Energy Intensity Relative to 2018 TRA			Wide Body			
			2018	2030	2040	2050–2070
T1	ATW-T1	Lower Progress	100.00%	96.27%	85.62%	78.89%
		Medium Progress		90.65%	77.98%	72.24%
		Higher Progress		83.30%	70.70%	65.93%

Table 1-4: Wide Body ACA Energy Intensity Deltas from The Respective ATW-T1 of the Same Year

ACA Energy Intensity Change Relative to Same Year's ATW			Wide Body			
			2018	2030	2040	2050–2070
T2	ACA-T2	Lower Progress			-5.00%	-5.00%
		Medium Progress			-10.00%	-10.00%
		Higher Progress			-15.00%	-20.00%
T3	ACA-T3	Lower Progress				40.00%
		Medium Progress				=ATW
		Higher Progress				-10.00%

Table 1-5: Wide Body Market Shares for New Entry and Replacements

Market Share for New Deliveries		Wide Body					
		2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	95%	50%	25%	0%
	ACA-T2			5%	50%	75%	100%
IS3	ATW-T1	100%	100%	95%	45%	10%	0%
	ACA-T2			5%	50%	50%	50%
	ACA-T3				5%	40%	50%

While the three tables above completed the data requirements needed for MDG, plots of the data in these tables were also generated as waypoints in the relevant years to better visualize the data trends and fleet changes. The first two plots below are representative figures for the wide body vehicle class with waypoints indicated out to 2050 at the three lower, medium, and higher progress levels. The first plot (Figure 1-3) includes the actual energy intensity values and the second (Figure 1-4) has the normalized percentage comparison of those energy intensities to the 2018 TRA. The third (Figure 1-5) and last figure below depicts the wide body vehicle class market share split over time from 2018 out to 2070 for all three Integrated Scenarios IS1, IS2, and IS3. The corresponding figures for all five vehicle classes are provided in sections APPENDIX M3.6 of this report.

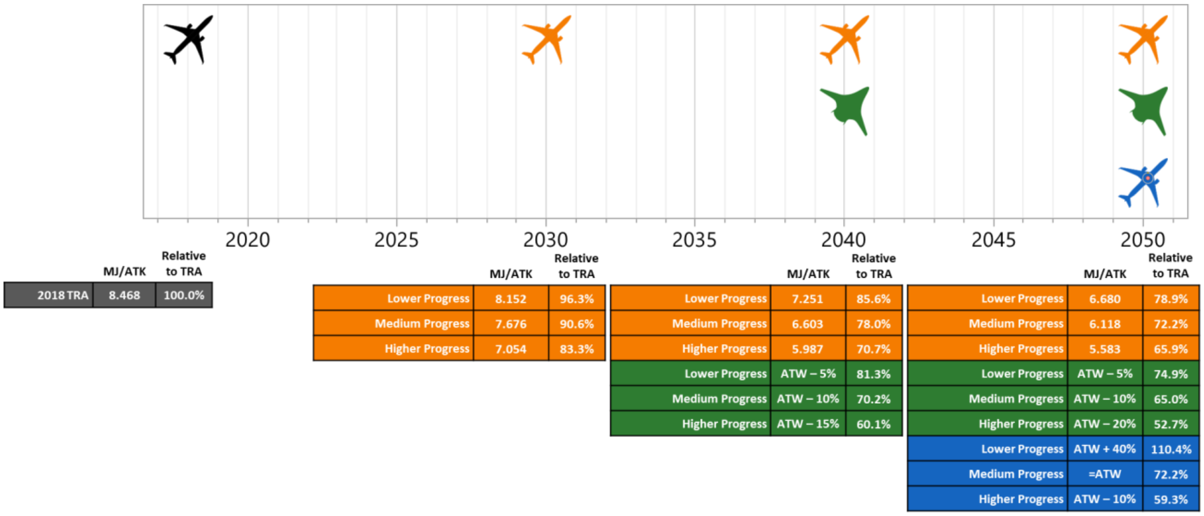


Figure 1-3: Wide Body ATW Waypoints, ACA Entry Into Service and Energy Intensity Values

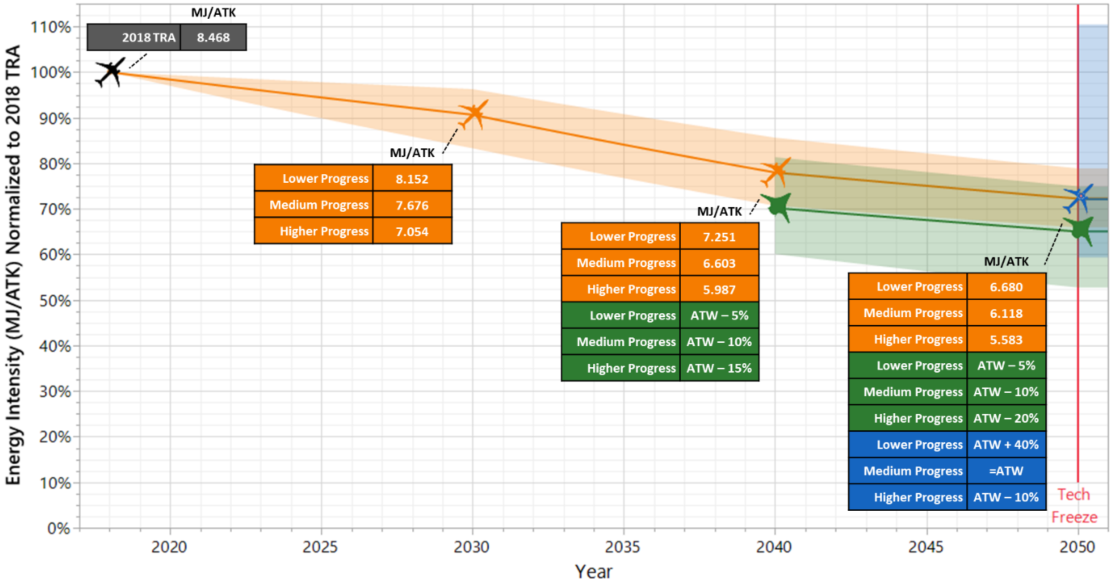
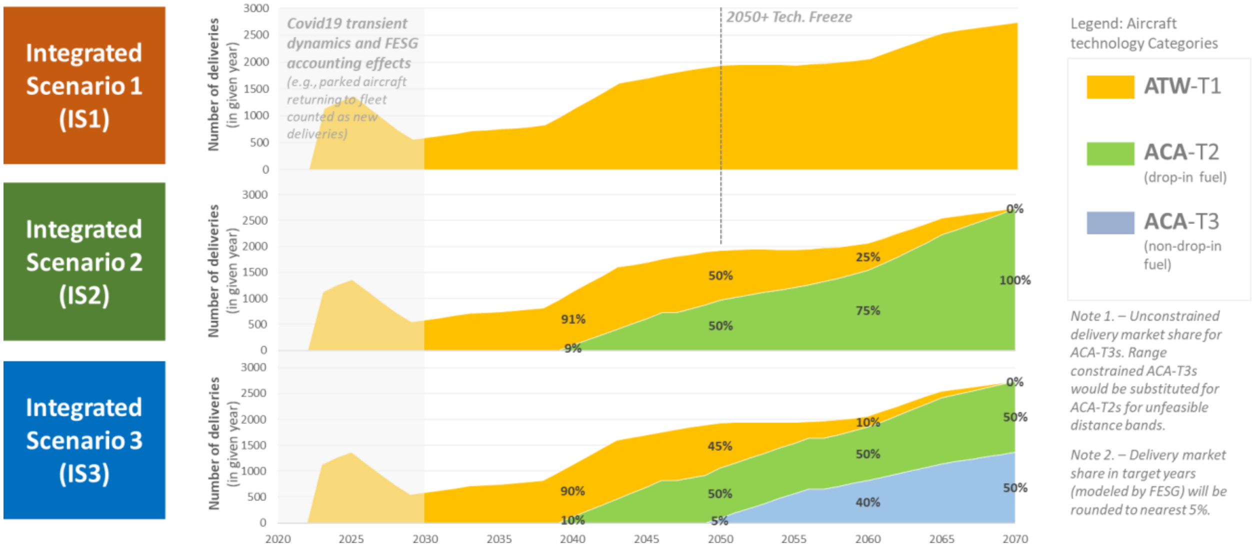


Figure 1-4: Wide Body Technology and Concept Energy Intensity Trend Normalized to the 2018 TRA



Note 1. – Unconstrained delivery market share for ACA-T3s. Range constrained ACA-T3s would be substituted for ACA-T2s for unfeasible distance bands.

Note 2. – Delivery market share in target years (modeled by FESG) will be rounded to nearest 5%.

Figure 1-5: Market Share Timeline for Wide Body Class of Vehicles

APPENDIX M3.2. INTRODUCTION

2.1 ROLE OF THE TECHNOLOGY SUBGROUP

The role of the Technology Sub-group (Tech SG) within LTAG-TG is to assess the potential of new and evolutionary technologies for airframes, propulsion systems and advanced concepts (including energy storage) to reduce CO_2 emissions between now and 2050. The LTAG Technology Sub-group is led by Dimitri Mavris, nominated by the United States, and by Wendy Bailey, nominated by Canada. Dimitri Mavris is the Director of Aerospace Systems Design Laboratory at the School of Aerospace Engineering at the Georgia Institute of Technology and was the Co-Chair of the Independent Experts Integrated Technology Goals Assessment and Review Panel for CAEP and author of the subsequent report. Wendy Bailey is the Chief of Environmental Protection and Standards in Civil Aviation at Transport Canada and is Canada's CAEP Member. The Technology Sub-group has 102 members nominated by CAEP Member States and Observers.

2.2 TECH SG ORGANIZATION

Five Technology Ad Hoc Groups (Tahgs) were created to organize the work of the Tech Sub-group: the Airframe Ad Hoc Group (35 members), the Propulsion Ad Hoc Group (39 members), the Advanced Concepts and Energy Storage (ACES) Ad Hoc Group (75 members), the Vehicle Impact Assessment (VIA) Ad Hoc Group (36 members), and the Modeling and Simulation (M&S) Ad Hoc Group (36 members). Four of the Tahgs have two focal points (co-Leads), one nominated by a State and one by an International Organization. The Airframe Tahg is led by Michelle Kirby (Georgia Tech, nominated by the United States) and Paul Vijgen (Boeing, nominated by ICCAIA). The Propulsion Tahg is led by Arthur Orton (FAA, nominated by the United States) and Andrew Murphy (Pratt & Whitney, nominated by ICCAIA). The Advanced Concepts and Energy Storage Tahg (ACES) is led by Rich Wahls (NASA, nominated by the United States) and Thomas Roetger (ZHAW, nominated by Switzerland, formerly IATA). Lastly, the Vehicle Impact Assessment Tahg (VIA) is led by Artur Mirzoyan (Central Institute of Aviation Motors, nominated by the Russian Federation) and by Eric Maury (Airbus, nominated by ICCAIA). Dimitri Mavris led the M&S Tahg.

2.3 TECH SG RESOURCE REQUIREMENTS AND COLLABORATION

A significant level of resources was required to meet the objectives and timeline of the LTAG. The Tech SG held 38 plenary virtual calls between May 2020 and January 2022. In addition, a three-day virtual Technology Interchange meeting was held on June 22-24, 2020 and an additional three-day virtual workshop focusing on the ACES Tahg over three weeks in December 2020. Due to the large workload and compressed schedule towards CAEP/12, additional calls were scheduled for each of the Tahgs, attended by the respective Tahg team members, in addition to smaller focus group meetings to resolve methodology items. The Airframe and Propulsion Tahgs had regular joint bi-weekly calls, and the ACES and VIA Tahgs had joint weekly calls through September 2020, then ACES had weekly calls through January 2021, and bi-weekly calls since then to allow for some work progress between calls. The M&S Tahg was formed October 2020 to focus on the modelling work related to the vehicle impact assessment and held biweekly calls since then, in addition to smaller group calls to focus modeling efforts on the turboprop class. Airframe had 13 calls, Propulsion 13 calls, ACES 29 calls, VIA 15 calls, and M&S 24 calls leading up to the CAEP/12 meeting. This listing does not include a multitude of additional calls that were conducted with smaller non-regular groups as needed and collaboration efforts. The co-Leads recognize the need for collaboration and coordination with the broader LTAG-TG, in addition to other CAEP Working Groups, including WG3, MDG, FESG, FTG, and ISG. In addition, the co-Leads had a series of calls with MDG and WG3 co-Rapporteurs to gain insight to the fleet level assessment data needs required from the Tech SG.

2.4 OVERALL TECH SG METHODOLOGY

To assess the CO_2 reduction potentials in 2050, the Tech SG identified the most recent Independent Expert Integrated Review (2019 IEIR) report as a foundation for the methodology developed herein. The IEIR methodology was adapted for the purposes of the LTAG remit to focus on CO_2 reduction potential, in lieu of interdependencies of noise, emissions, and CO_2. From a high-level perspective, this included four main steps, establishment of technology reference aircraft (TRA), assessment of advanced tube and wing (ATW) configurations, assessment of advanced concept aircraft (ACA), and generation of the necessary information for the fleet-wide modeling and cost assessment. Each of these steps are briefly discussed here and will be described in detail in subsequent chapters.

From the IEIR study, the Tech SG agreed on the 2019-IEIR TRA as a basis for the analysis. The TRAs available are Business Jet, Regional Jet, Narrow Body and Wide Bidy Aircraft. The group agreed to move forward with the four TRAs from a conventional configuration perspective, but to also add a notional turboprop aircraft as a fifth TRA, which serves as a foundation for study of alternative energy sources that could be available. The focus of the Tahg's was to determine the additional benefits above and beyond the IEIR projections for 2037 to a 2050 timeframe for each of the TRA's (relative to 2018 TRA's) to determine the level of improvements for ATW configurations. For each TRA class, a three-point estimate for each airframe and propulsion technology area was provided to the M&S Tahg, which were defined as higher progress (most aggressive technology level), medium progress (nominal technology level), and lower progress (lowest technology level).

The five Tahgs reviewed the relevant submitted Stocktaking Questionnaires in the ICAO Virtual Library and identified what gaps in data exist to support proper assessment of future technology opportunities. Given the limited data in the submitted Questionnaires, each of the Tahgs conducted a literature review to identify the possible technologies and advanced configurations possible to support the Tech SG effort with credible studies and other public sources, in addition to reaching out to international research institutes on recent ACA studies conducted within the classes of aircraft under consideration. The Tahgs collectively agreed that the primary starting point for the ATW and ACA projections to 2050 was the 2019 IEIR report.

The vehicle-modelling approach utilized in the 2019-IEIR with the use of the Georgia Institute of Technology modeling capabilities for conventional aircraft was agreed to for the five TRAs to establish the ATW configurations for 2030, 2040, and 2050. The airframe and propulsion Tahgs provided input for the design constraints and variables to utilize for each class of ATW for each time frame. The ACA modelling approach was agreed to be qualitative and relied on previous high-quality published studies to establish the improvement above and beyond future ATWs.

ACES established a series of configurations for potential consideration across the five vehicle classes, for either a quantitative or a qualitative assessment. These ACAs included (but were not limited to) blended wing bodies, truss-braced wings, and supersonic aircraft, and incorporating alternative propulsion systems based on non-drop-in energy, such as electricity or hydrogen. ACES carried out an assessment process for the ACAs, consisting of the following steps: (a) Configuration/ architecture screening based on potential benefits per scenario, (b) Technical and non-technical barrier identification, (c) Assessment of advanced aircraft concepts through scorecards, (d) Identification of representative notional aircraft concepts for each class, (e) Vehicle level benefit quantification (compared to same-year ATW), (f) Technology and vehicle scenario-based projection (fleet penetration), and (g) Cost estimation and investment quantification.

Two overlapping ACA "baskets" of innovation were considered beyond the ATW, which uses conventional or drop-in fuel: ACA T2 is representative of alternative architecture airframes and/or propulsion (with conventional or drop-in fuels), and ACA T3 is representative of advanced airframes and advanced propulsion characterized by the use of non-drop-in fuels with or without alternative airframe architecture changes. Note that an ATW configuration with non-drop-in fuels would also be considered as an ACA T3 alternative. The qualifiers "T2" and "T3" indicate a system of three technology levels or alternatives: T1 including ATWs only, T2 including the addition of ACAs with conventional or drop-in fuels and T3 which includes all advanced aircraft including ACAs with and without non-drop-in fuels.

In collaboration with the other LTAG Sub-Groups, three integrated scenarios (IS#) were defined for the LTAG analysis. For each scenario, Tech SG provides a summary table for each of the five aircraft classes under consideration. Each summary table included the following information:

- For IS1: T1: Advanced Tube & Wing (ATW) per annum energy efficiency improvements relative to ATW of previous decade at three progress levels (lower, medium, higher) for 2030, 2040, and 2050
- For IS2: T2: Advanced Concept Aircraft (ACA) energy efficiency improvements relative to same year ATW at three progress levels (lower, medium, higher) for applicable timeframes
- For IS3: T3: Advanced Concept Aircraft (ACA) energy efficiency improvements relative to same year ATW at three progress levels (lower, medium, higher) for applicable timeframes
- Range and payload information for all ATWs and ACAs, and applicable competition bins
- New Aircraft Market Share (production/introduction) of ACAs vs ATWs for 2018-2070

The remainder of the appendix is dedicated to the execution of the Tech SG methodology and will be described in detail.

APPENDIX M3.3. TECHNOLOGY REFERENCE AIRCRAFT DEFINITION AND MODELING APPROACH

3.1 INTRODUCTION

This chapter provides an overview of the modeling conducted for this LTAG led process and a summary of the technology reference aircraft used as the basis for the goal setting. Next, the modeling and simulation environment utilized for the quantitative assessments is discussed along with the resulting Technology Reference Aircraft (TRA) baseline models.

3.2 AIRCRAFT CATEGORY SELECTION AND CONSIDERATIONS

MDG/FESG uses generic aircraft categories in its forecast and fleet evolution analysis and has defined these different categories by seat capacities:

• Business Jet (BJ)	≤20 seats
• Turboprop (TP)	20-85 seats
• Regional Jet (RJ)	20-100 seats
• Narrow Body (NB)	101-210 seats
• Wide Body (WB)	> 210 seats

The reference aircraft have been chosen to represent the five major categories of aircraft in service in 2018. Originally, the plan was to use generic (i.e. hypothetical) Technology Reference Aircraft (TRA) representative of aircraft in service in 2018 so as to avoid competitive issues. However, to ensure the availability and consistency of input data and to allow International Coordinating Council of Aerospace Industries Associations (ICCAIA) to provide an assessment of the baseline, notional representations of the most recently certified aircraft fitting as closely as possible into each class were used as notional references. Also, by using actual as opposed to generic aircraft, the different participating organizations were in a position to provide additional data points that could be used to establish the reference aircraft. The Tech SG agreed to utilize the IEIR models with the addition of the turboprop class for the purpose of LTAG. The reference aircraft selected, with guidance from ICCAIA, were:

• BJ	Notional G650ER
• TP	Notional DHC Dash 8-400
• RJ	Notional E190E2
• NB	Notional A320neo
• WB	Notional A350-900

It became apparent during the review that the division between RJ and NB aircraft was blurred because RJs, such as the Embraer 190 and the Airbus A220 (formerly the Bombardier C-series), now have over 100 passengers and could be classed as a small NB. Likewise, a large BJ like the G650ER is comparable in size (specifically with respect to maximum takeoff mass, MTOM) to some smaller RJs, although the speeds, range and payload capacity differ. All available public domain information on the notional aircraft, and industry provided additional performance information, were used to form the basis of the modeling.

3.3 MODELING AND SIMULATION METHODOLOGY

A modeling and simulation capability was required to assess the impacts of the technologies for the three-time frames. The Aerospace Systems Design Laboratory in the Georgia Institute of Technology (GT/ASDL) was engaged to assist the Tech SG in a modeling capacity [5]. The foundation for this systems analysis capability is the advanced methods developed at GT/ASDL coupled with an integrated aircraft modeling and simulation environment known as the Environmental Design Space (EDS). EDS is capable of predicting the fuel burn, NO_x emissions, and noise metrics in a single environment with an automated link to provide necessary data for the LTAG assessment (see Figure 3-1).

The majority of the EDS analysis components are NASA developed programs. EDS is capable of modeling the thermodynamic performance (NASA's NPSS) of any engine cycle coupled with a parametric component map generation tool (NASA's CMPGEN) and with a 1-D aeromechanical design/analysis for flowpath and weight estimation purposes (NASA's WATE++). This propulsion system simulation is well suited to assess the IEIR technology portfolio and in its ability to match the engine to a sized airframe using a simultaneous, multi-design-point sizing algorithm developed by GT/ASDL. The propulsion simulation module is coupled with the mission analysis module (NASA's FLOPS) in an iterative fashion, to ensure that all coupling variables are internally consistent and have converged, and then passes information to the noise prediction module (NASA's ANOPP). These are used to assess acoustic impacts, including the generation of engine state tables from NPSS and the resulting aircraft noise flight trajectories for the sized vehicle. This data is used within ANOPP to generate the three certification noise values for sideline, cutback and approach as well as characteristic noise power distance (NPD) curves. Further details on the components of EDS are described in Annex B.

The EDS environment executes four phases for each simulation run representing a single vehicle system.

- Phase 1: EDS Initialization Phase
    - Establishes the different options for running EDS (e.g. WB, NB, RJ, TP, or BJ)
    - Determines the settings of the design variables
- Phase 2: Vehicle Design Phase
    - Depending on the desired design there can be a design iteration for the engine and a design iteration between the engine and airframe
    - The vehicle size and weights are fixed at the end of this phase
- Phase 3: Vehicle Performance Evaluation Phase
    - In this phase all desired performance evaluation is conducted including gaseous emissions, noise certification, takeoff and landing performance, and fuel burn for off design points on the payload-range chart
- Phase 4: Output Data Phase
    - All desired data is compiled into user-specified summary files.

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5 The GT/ASDL has over 20 years of experience in the area of system-level analysis of current and advanced vehicle concepts and technology portfolios. GT/ASDL has used the EDS to assess unconventional aircraft and propulsion systems in support of the NASA Fixed Wing (FW), FAA Continuous Lower Energy, Emissions, and Noise (CLEEN), NASA Environmentally Responsible Aviation (ERA), and NASA Vehicle Systems programs. Within the context of the NASA FW project, GT/ASDL created integrated models of NASA's N3-X concept (distributed turboelectric, boundary layer ingestion), the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) truss-braced wing (hybrid-electric), and the MIT double bubble (with boundary layer ingestion).

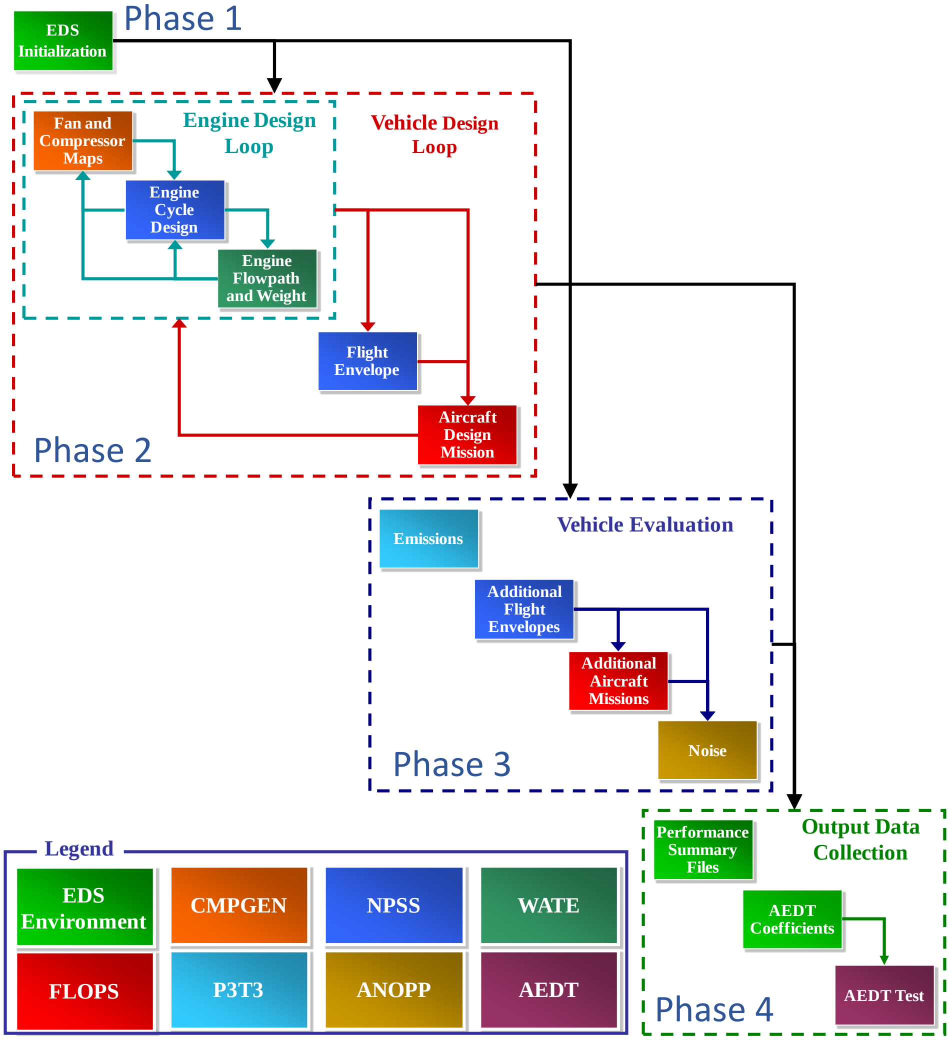

Figure 3-1. Environmental Design Space (EDS)

EDS uses a simultaneous, multi-design point method to generate the engine cycle, which means EDS converges on the following five design points simultaneously:

- Point 1, ADP (Aero Design Point)
  - Reference point used to define the performance of the turbomachinery components
  - Typically, at cruise conditions for commercial aircraft systems
- Point 2, TOC (Top of Climb)
  - Thrust point established by airframe requirements. Sets maximum mass flow and corrected speed of the engine. Maximum T_{40} could occur at this condition for BJ
- Point 3, TKO (Take Off)
  - Another thrust point established at aircraft rotation. Maximum T_{40} specified at this condition for high BPR engines.
- Point 4, SLS Installed

  - Constraint point to ensure that flat rated thrust can be achieved. This point cannot exceed maximum T_{40} allowable.
- Point 5, SLS Uninstalled Thrust
  - ICAO emissions point for turbofan engines, which sets the maximum SLS thrust (used for D_p/F_{oo}). Maximum SLS thrust is minimum of thrust generated at Nc = 100% or $T_{40} = T_{40max}$

EDS, like most conceptual sizing and synthesis design tools, uses physical performance constraints in both the engine and airframe analyses to ensure the resulting model is a feasible design. Two additional constraints were recommended by ICCAIA to the GT/ASDL team, specifically, engine ground clearance and wingspan (gate) constraints, where the values utilized for the study are contained in Annex E. The following list enumerates the additional constraints used within EDS for all aircraft:

- Minimum rate of climb (300 ft/min) excess power at top of climb
- Turbine material limits (T_{4max}/cooling flow)
- Compressor material limits (T_3 limits)
- Thrust (or power) requirements for critical points in the mission
- Fuel capacity volume must be available
- Service ceiling constraint
- Take-off/Landing constraints (field-length, obstacle height, one engine out, etc.)
- Reserve mission fuel requirement

3.4 TECHNOLOGY REFERENCE AIRCRAFT

The technology reference aircraft (TRA) were simulated within EDS based on public-domain available data and are representative of the five aircraft listed in Section 3.2. An iterative process was utilized to fine tune the notional aircraft modeling with guidance and feedback from ICCAIA to provide performance consistent with published information. The result was five TRAs upon which the technology area impacts could be inserted onto a given aircraft for 2030, 2040, and 2050.

The TRA models utilized aircraft geometry, mass, mission, and propulsion characteristics. Publicly available manufacturer data, where available, took precedence over other sources because of its greater accuracy. This data was taken from airport planning documents, CAD drawings, and brochures. Aircraft geometries were derived from manufacturer CAD drawings, where available, and aircraft masses were taken from airport planning documents. In the absence of publicly available manufacturer data, the Piano database (a professionally recognized tool for analyzing commercial aircraft) was used. The models were then calibrated to match this data.

The calibration process had two phases, one to calibrate the engine model and the second to calibrate the airframe model. The first phase required that a nominal engine be created to simulate a mission, and this was calibrated using a combination of publicly available manufacturer data and ICAO emissions databank data. The manufacturers' data included information such as OPR, fan diameter, number of stages, etc. The notional model matched ICAO reported fuel flow and thrust levels.

The mission analysis model, FLOPS, was calibrated in two steps, one for each of its operating modes: mission analysis of a fixed aircraft (an aircraft of defined geometry and size) or sizing an aircraft for a specified mission. The first step was to calibrate the aerodynamic module of the aircraft using the fixed mode. This yielded aircraft maximum take-off mass (MTOM), fuel mass, operational empty mass, and design payload for the aircraft's design range. The design fuel and payload mass were derived from aircraft payload range charts from the manufacturer's airport planning documents, where available, based on a typical seating class.

To illustrate this process, consider the information provided by Embraer's airport planning document for the E-Jets E2 (APM – 5824, revision 16, dated February 07 of 2020). The document shows three potential seating arrangements for the E190-E2: 104 pax (single class, 31 in pitch), 114 pax (single class, 29 in pitch), and 96 pax (dual class, 38/31 in pitch). Then, the payload-range diagram for this aircraft class (PW1922G engines, MTOW = 56,400 kg) shows that, for a 0.78 Mach cruise at 37,000 ft, the R2 payload-range are 9,600 kg and 3,350 nmi, respectively. It becomes clear that, for the dual-class configuration with 96 pax, this yields a passenger mass of 100 kg, which is approximated to 220 lbm per pax for modeling purposes. This process was repeated for each TRA to determine their respective number of passengers and design payload.

Within the payload-range diagram of a given TRA, the design point utilized for this assessment would typically be for a range near the R_2 range, as depicted in Figure 3-2. Assuming a mass per passenger and an OEW, the design range could be inferred from the actual aircraft's payload-range envelope. The R_1 range would be utilized for the optimization of the advanced tube and wings, which is the range at the maximum structural payload.

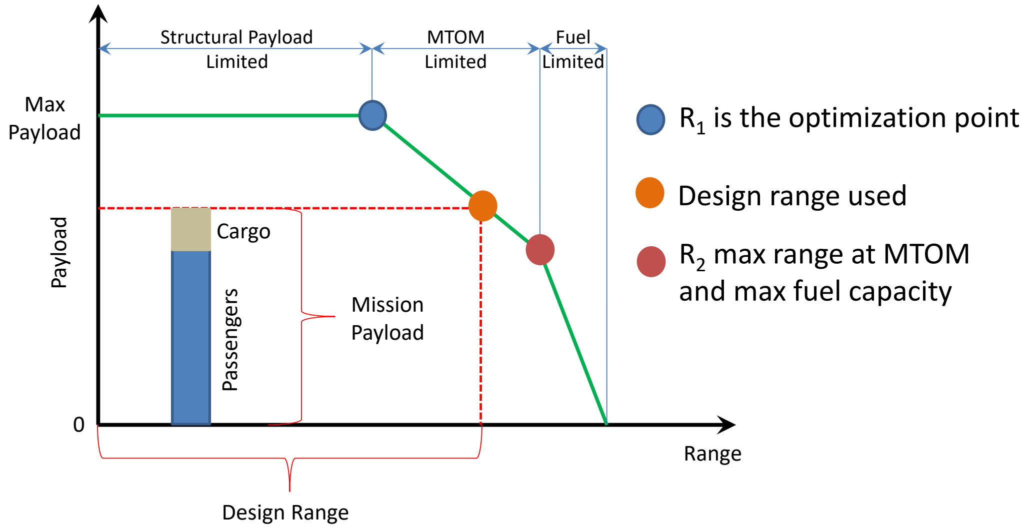

Figure 3-2. Typical Payload Range Diagram

Once the aerodynamic parameters were calibrated, the second mode of FLOPS was employed. Using the same design mission, scaling factors were used to match information from the Piano database. The calibration consisted of setting component mass scaling factors to match information from the Piano database. After the mass scaling factors were set, these results were verified by performing the analysis again using inputs for the thrust-to-weight ratio at take-off and wing loading. This calibration process verified that the results from EDS would match TRA data. The details of the five TRAs are described briefly below. All were analyzed with EDS and the detailed results are presented in Annex C.

It should be noted that the calibration process utilized fuel burn as a matching parameter in lieu of the CO_2 metric value, since that data is yet to be made publicly available. The actual CO_2 Standard certification data is expected to emerge piecemeal over the next 5-10 years. When these data are available, it will allow further confirmation of the modeled 2018 TRA aircraft fuel burn performance. However, for optimizing the performance of the aircraft, the fuel burn metric has advantages because it correctly uses the physical parameters, specifically fuel burned normalized by payload times distance carried, and is proportional to a rational definition of efficiency.

3.4.1 Turboprop Technology Reference Aircraft

The TP TRA is based on a notional De Havilland Canada Dash 8-400. The assumed payload is 16,650 lbm, carrying 74 passengers at 225 lbm each (including baggage weight) at the design range [6] of 1,100 nm on the payload-range diagram, which corresponds to maximum fuel capacity and mass at take-off, which is at a slightly shorter range than the R_2 condition (this is the case for all other TRAs). The design cruise Mach number is 0.50 and the maximum cruise altitude is 25,000 ft.

3.4.2 Business Jet Technology Reference Aircraft

The BJ TRA is based on a notional Gulfstream G650ER. The assumed payload is 1,800 lbm, carrying 8 passengers at 225 lbm each at the design range of 7500 nm. The design cruise Mach number is 0.85 and the maximum cruise altitude is 51,000 ft.

3.4.3 Regional Jet Technology Reference Aircraft

The RJ TRA is based on a notional Embraer E190-E2. The assumed payload is 21,120 lbm, carrying 96 passengers at 220 lbm each at a design range of 3,350 nm. The design cruise condition is at Mach 0.78 and the maximum cruise altitude is 41,000 ft.

3.4.4 Narrow Body Technology Reference Aircraft

The NB TRA is based on a notional Airbus A320neo. The assumed payload is 33,750 lbm, carrying 150 passengers at 225 lbm each at a design range of 3,360 nm. The design cruise condition is at Mach 0.78 and the maximum cruise altitude is 41,000 ft.

3.4.5 Wide Body Technology Reference Aircraft

The WB TRA is based on a notional Airbus A350-900. The assumed payload is 68,250 lbm carrying 325 passengers at 210 lbm each at a design range of 8,000 nm. The design cruise condition is at Mach 0.85 and the maximum cruise altitude is 43,000 ft.

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[6] The typical payload or passengers carried quoted by the manufacturers was utilized at the design range, which falls on the constant volume line of the payload-range diagram between the R_1 and R_2 ranges. R_2 range is maximum range for take-off with maximum take-off mass at maximum fuel capacity, whereas R_1 range is maximum range for take-off with maximum payload and maximum take-off mass.

APPENDIX M3.4. AIRCRAFT FUEL BURN AND CO_2 REDUCTION

4.1 INTRODUCTION

Improvements in aerodynamic, systems, structures and materials, as well as propulsion technologies have a direct link to aircraft CO_2 emissions and are key to achieving future aircraft CO_2 reduction goals. In the past decade, additional advanced long-range twin-aisle airplanes with significant improvements in these technology areas have entered operational service (the Boeing 787-9 and -10, the Airbus A350-900 and -1000), while the new Boeing B777-9 aircraft with a completely new composite wing is progressing certification testing. Moreover, several recently introduced new single-aisle aircraft (such as the Airbus A220-100 and -300) and several derivative aircraft with major propulsion and airframe technology upgrades (such as the Airbus A320neo, A321XLR and A330neo, the Boeing B737MAX family, and the Embraer E-Jets E2), have entered operational airline service and provide substantial reductions in fuel burn. The specific technologies and capabilities which underpin these aircraft, to the extent they are shared in the public domain, represent the state of the art in larger sized turbofan aircraft design and hence the reference for various new developments underway or approaching completion around the world – for instance in China (C919), Japan (Spacejet) and Russia (MC21). These technologies and capabilities have also been brought forward in the latest new and derivative business jets from manufacturers Bombardier (Global 7500), Dassault (Falcon 8X) and Gulfstream (G650 and more recent G700).

Large-scale national and international research programs with cooperation between industry, government and academia continue to be key enablers to advance and mature the state of art in breakthrough integrated technologies that can lead to further reduction in aviation's environmental footprint. Flight demonstrators offer important technical and integration data to progress technologies such as laminar flow, and advanced structural designs as well as more electric systems and more electrical propulsion.

The integration and certification challenges associated with advanced technologies are significant New technologies need time to mature and be ready for adoption into new or derivative aircraft products. The maturation alone can require up to 10-20 years, with further time required even after TRL 6 before the proven technology can be integrated in a product and put into service. The maturation and adoption of the key technologies summarized in this Chapter would provide significant additional opportunities to reduce aeronautical emissions, assuming they are successfully progressed through to and beyond TRL 6 maturity. The definitions of the TRL scale are provided in Annex A.

4.2 AIRCRAFT AERODYNAMIC EFFICIENCY IMPROVEMENT OPPORTUNITIES (AIRFRAME TAHG)

Viscous drag and lift-dependent drag are the largest drivers of the aerodynamic efficiency of commercial aircraft. Several technology improvements are being progressed towards possible practical application in both areas. The applicability and maturation potential of several technologies are different for the various aircraft TRA classes. As a result, projected technology opportunities for viscous and lift-dependent drag reduction are not identical between the TRA classes. This section summarizes key aspects of flow-physics and integration constraints and opportunities for potential aerodynamic technologies.

4.2.1 Lift Dependent / Induced Drag Reduction Technologies

Advances in materials, structures and aerodynamics can enable significantly reduced lift-dependent drag by increasing effective wing span, such that many aircraft designs now feature true wing spans at or approaching the gate category limits specified by ICAO. In response, the adoption of some form of wing-tip device – be it substantially in the plane of the wing, or rising from the plane (classical winglet) or featuring upward and downward pointing element – has become a standard part of wing design. The essential technical role of such devices is to increase wing effective span whilst maintaining acceptable wing loading and aerodynamic interference consequences. The resulting benefits may be seen not just in fuel burn through cruise drag reduction, but also in improved climb performance with implications for aircraft noise and/or engine wear. To further increase wing span in flight some airplanes may include a folding wing-tip mechanism for use on the ground to mitigate the span constraints of existing airport infrastructure, as depicted in Figure 4-1.

Dramatic increases in wing span may be enabled by novel configurations, such as the TTBW concept, as described in APPENDIX M3.6. Such concepts may require moving wing tips to facilitate ground operations as well as incorporation of advanced load-alleviation technology during flight. Load alleviation methods that may enable increased (effective) wing span are further described below.

Figure 4-1. On-ground folding wing tip to maximize in-flight wing span (Boeing B777-9)

(Image courtesy Boeing)

4.2.2 Viscous Drag Reduction Technologies

Viscous drag due to profile and skin-friction drag generally is the largest drag component for conventional aircraft configurations. Minimizing the wetted area of the aircraft and tailoring aerodynamic design to minimize flow separation as much as possible in key flight conditions is a basic principle of aerodynamic design to reduce viscous drag. Over last decades, significant progress is being made in development, maturation and introduction of practical aerodynamic and manufacturing technologies that enable reduced skin friction through maintaining laminar flow and/or conditioned turbulent boundary-layer flow on portions of wings, nacelles, tails, and fuselages.

Methods to apply robust micro-scale ‘riblet’ geometries for turbulent-flow skin-friction reduction continue to be developed and tested to progress maturation to practicality. Estimates suggest opportunities on order of net 1- 2% fuel-burn reduction on new and existing aircraft with significant areas covered by practical ‘riblets’. The extra weight of riblet appliques somewhat reduces the fuel-burn benefit provided by riblet turbulent profile drag reductions. Whilst the flow-physics principles of turbulent drag reduction via riblet-like micro-scale surface shaping are understood to allow design and scaling, traditionally there have been significant practical challenges to manufacture, install and maintain such surfaces for airline operations. Nonetheless, a level of research has been maintained in this area looking at both maximizing the potential savings from riblets and/or easing their application and maintenance.

More significant reduction in skin-friction drag is possible by achieving and maintaining laminar flow on forward areas of engine nacelles, wings and tails. Surfaces intended for Natural Laminar Flow (NLF) are already present on some in-production commercial and business-jet aircraft (e.g. nacelle-inlet lip and winglets on some larger aircraft, and portions of wing and fuselage on some business jets). Achieving the potential for laminar flow on aircraft surfaces requires well-balanced aerodynamics and structural designs together with aligned manufacturing methods to ensure the necessary surface quality and pressure distributions under real flight conditions.

Research and developmental flight testing of integrated wing structures that offer substantial areas of laminar flow as well as allow high-rate production are critical for technology maturation. Within the European Clean-Sky 2 Program [7], the BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe) project has delivered important data on such NLF wing design concepts. Flight tests conducted on an Airbus A340-300 (with modified outer wings that are built to enable NLF) explored limits of robust laminar flow at various flight conditions, as depicted in Figure 4-2. These tests have re-confirmed the viability of achieving long runs of laminar flow over representatively manufactured aero structures and have broken ground in terms of tolerance relaxation relative to the tolerance demands inferred from earlier academic work. Nevertheless, significant further work will need to be done and challenges will need to be overcome in the area of NLF before widespread exploitation will be commonplace on larger aircraft used in airline service. Several business jets and general-aviation aircraft already employ designs and manufacturing to enable NLF on lifting surfaces, winglets, nacelle inlet lips – as well as on forward portions of fuselage.

Beyond the challenge of designing and successfully manufacturing aircraft with NLF potential, there lies the challenge of achieving the designed extents of laminarity in routine operations, in particular where aircraft surfaces may be subject to contamination by insect residues, or other forms of dirt or ice accretion. There is active research in this area looking at anti-contamination surface coatings. The exploitation of shielding provided by suitably designed leading-edge high-lift devices, such as Krueger flaps, may also be considered for lifting surfaces, although such approaches are not applicable in other areas such as nacelle intake lips.

Figure 4-2. Integrated wing NLF (Natural Laminar Flow) integration concepts installed on modified outboard wings of Airbus A340-300 (Clean-Sky 2 flight demonstrator BLADE)

(Image courtesy Airbus)

On wings of very large aircraft and on geometries with significant sweep such as a vertical fin, laminar flow can only be realized using suitable surface suction (Hybrid Laminar Flow Control, HLFC). Recent flight testing of a vertical-fin HLFC configuration on a single-aisle aircraft under the European AFloNext (Active Flow, Loads and Noise control on Next generation wing) program complements the first HLFC

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[7] https://www.cleansky.eu/smart-fixed-wing-aircraft-sfwa

application on the Boeing B787 tail, as depicted in Figure 4-3. As is the case with NLF, HLFC benefit is not given here for free; while significant progress has been made in simplifying the HLFC systems as demonstrated before 2000, the achievement of HLFC continues to require the addition of sophisticated parts and additional systems to the aircraft with implications for aircraft cost, weight, manufacturing tolerances for laminar flow, and operability – similar as for NLF applications. The HLFC drag increments have been adjusted to include drag penalties equivalent to the weight and power requirements involved in achieving the HLFC.

Figure 4-3. AFLoNext HLFC empennage flight test on DLR's A320 test aircraft

(Image courtesy DLR)

Overall, practical and robust achievement of significant laminar flow on wings and other surfaces could reduce aircraft fuel burn on the order of 5% for larger aircraft. The magnitude of the potential benefit depends on the fraction of the airplane surfaces manufactured to achieve laminar flow, the trade-off where applicable in terms of airframe weight, and the missions and operational conditions to which the airplane will be exposed. On smaller aircraft, lower chord Reynolds numbers may facilitate laminar flow robustness, however, the significantly larger number of take-offs and landings for turboprops and regional jets may result in larger insect contamination, reducing the effective average laminar-flow benefit. In addition, for aircraft with pneumatic wing ice-protection systems, the presence of "pneumatic booths" in the cruise wing leading edge will likely greatly limit the achievable extent of laminar-flow in view of laminar-flow surface tolerance requirements.

Beyond the efforts to reduce aircraft viscous drag through "broad brush" technologies distributed over large areas of the aircraft, further useful and cost-effective progress can also be made at the local level. This can be achieved in a traditional way through attention to excrescence drag, by minimizing the number of excrescence items (including antennas etc.) on the aircraft and by optimizing the design of those that are required considering both shaping and manufacture aspects. Here there is a key synergy with progress in manufacturing engineering and production technologies. However, additional potential may be provided through morphing structures, potentially allowing the elimination of some of the panel breaks seen on traditional aircraft structures which are required to allow the movement of traditional control surfaces. Replacement of such surfaces by morphing structures achieve the same functionality without panel breaks, although this potential may not be achievable for movables with a high-lift function where slotting is a key part of the high-lift functionality.

4.2.3 Integration and Simulation Technologies

In addition to the technologies so far mentioned directed at the largest drag terms for a particular aircraft, there is also an ever-important role for technologies and capabilities targeting drag due to shock waves, interference drag and other sources of drag coming from adverse boundary-layer behavior. A first and key line of attack in combating these drag terms comes through the ability to use Computational Fluid Dynamics (CFD) at will in the various stages in the aircraft design process, enabled by increases in computing power, in the CFD algorithms that are affordable, and in the complexity of configuration that can be meshed and solved. CFD methods that can model increasing levels of physical fidelity at local as well as complete-aircraft scale are used at different stages in the aircraft design process [8].

Particularly for the most recent long-range aircraft, operating at high Mach and Reynolds numbers with very adverse exchange rates between drag and weight, these methods have had a decisive impact on product performance. They will have a central role in the development of all future aircraft, especially where operational efficiency is paramount. That said, the level of improvement potential will vary from one class of aircraft to another, with some benefits achieved in recent years in the long-range aircraft sector likely to be difficult to transfer over into some of the smaller aircraft categories.

One major current area in the exploitation of CFD relates to its usage for improved design optimization. This may come through the hugely enriched information which can be fed to the human engineers in the multidisciplinary optimization (MDO) loop or through the automated coupling of CFD tools with tools from other disciplines to try to replicate and go beyond the potential of traditional, human-based, manually coupled design processes. Accordingly, it has been deemed appropriate to include figures for MDO – that is, aircraft improvement through better integration without regard to any particular technology – in the performance improvement figures quoted in the aerodynamics area. In particular, the use of composite materials and advanced load alleviation technology can result in increased wing aspect ratio (and span).

Limitations on what can currently be achieved through CFD and through CFD-based MDO should be noted. In particular, the progress to date in achieving efficient and highly accurate CFD capabilities has had a focus on cruise design where the imperative to achieve low drag typically demands robustly attached and benign flow over almost all the surfaces of the aircraft. By their nature, such flows are particularly amenable to accurate and efficient CFD analysis and optimization. A considerable mountain remains to be climbed in ensuring the validity of CFD for the much wider range of flow conditions which are important in achieving valid aircraft designs. There is an important and continuing role for high quality experimental wind-tunnel test capabilities to provide confidence in CFD analysis results in these wider areas of the flight envelope – in particular in conditions with strong shockwaves and significant flow separation (e.g. in presence of deflected control surfaces, an example is shown in Figure 4-4). There is also a role for international activities such as the AIAA High- Lift Prediction Workshop activity to address flow prediction in the particularly complex and critical low-speed performance envelope.

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8 Slotnick, J., and Heller G., Emerging Opportunities for Predictive CFD for Off-Design Commercial Airplane Flight Characteristics," Proceedings of the 54th 3AF International Conference on Applied Aerodynamics, 2019)

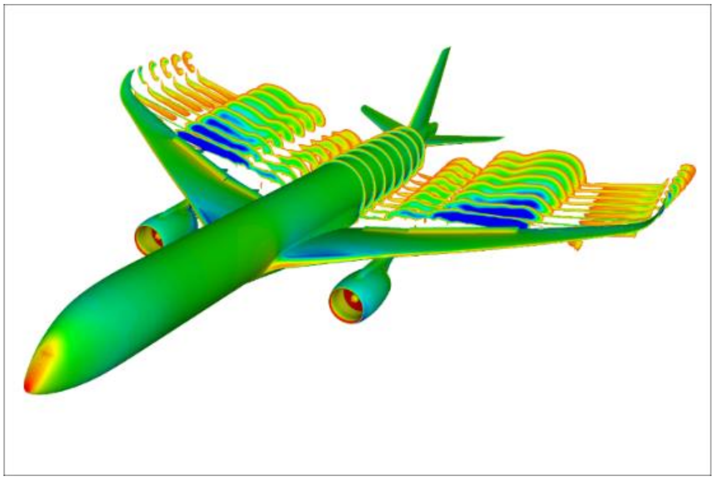

Figure 4-4. CFD Flow Simulation on wing with deflected control surfaces (Wide-Body Aircraft Configuration) (Image courtesy Airbus)

Returning to physical, as opposed to capability technologies, the types of benefits that can be targeted, thanks to high confidence in simulation capabilities, include:

- Maintaining and improving the state of the art in propulsion / airframe integration to ensure the benefits of the propulsion concepts of the next decades are not negated by adverse consequences for airframe drag.
- Correspondingly, the ability to look at concepts such as short nacelles aimed at minimizing the upward creep in friction drag which is associated with even larger engine diameters. Such concepts can only be adopted so long as their implications at all flight conditions can be understood and optimized at the design stage – considering, for instance, crossflow conditions on the ground.
- Giving confidence to adopt a novel propulsion concept such as boundary-layer ingestion – as can be seen in a number of research investigations in recent years.
- The full exploitation of variable camber and multifunctional trailing edge systems to manage in flight loading distributions (linked to structural loading but also induced drag) and in-flight camber (controlling drag due to shock waves).
- The adoption of morphing technologies to enable the in-flight adaptation of aircraft shape to current flight conditions as an extension of, or complement to, the application of variable trailing edge camber. Several modern wide-body aircraft already incorporate cruise trailing-edge variable camber technology where the position (small deflections) of the flaps and ailerons are adjusted at regular intervals in cruising flight to minimize total drag.

Lastly, Active Flow Control (AFC) should be mentioned as a key potential technology in addressing aircraft interference and boundary-layer phenomena. At this time, many AFC technologies have remained squarely on the low maturity side of the “TRL valley” over a number of decades, albeit with continued demonstration of their theoretical benefits at bench test level. However, there have been significant and tangible maturation steps in the past decade including the achievements of Boeing’s EcoDemonstrator program and activities in Europe as part of AFLoNext. Localized suction and/or blowing systems have demonstrated the potential for increased control surface effectiveness through delayed separation (with the potential to snowball through to reduced tails sizing and reduced skin friction drag) and improved high-lift performance again through delayed flow separation in the wing / pylon junction (with the potential to snowball through to enabling the integration of larger turbofan engines with minimized high lift penalties).

AFC technologies require close integration with Systems and Propulsion technologies to reliably provide (and account for) energy required to power the AFC actuators at key conditions.

4.2.4 Aggregation of the Aerodynamic Benefits

For each of the TRA configurations, aerodynamic increments were assembled in various technology categories and aggregated into induced-drag and viscous-drag improvement terms by the Airframe Technology Ad-Hoc Group. Inputs from available ICAO stocktaking events were reviewed and technologies not yet assumed were incorporated with consideration of the increments they might practically achieve. The aerodynamic technology benefits for flow control techniques were corrected to net benefits after drag penalties equivalent to assumed weight effects and power demands had been subtracted.

The increments in Annex D in this LTAG report differ between the five TRA configurations in assessed magnitude of achievable, practical and certifiable application of the various potential technologies. Both logical and quantitative factors were considered:

- Logical: for example, avoiding both natural laminar and hybrid laminar increments being applied to the same component of the TRA
- Quantitative: for example, recognizing the greater potential for excrescence drag reduction on (typically smaller) aircraft with higher percentage levels of excrescence drag than on (typically larger) aircraft with lower percentage levels of excrescence drag.

In addition to a nominal technology projection for the various future decades relative to the reference TRA configuration, estimates are provided at lower-progress (higher likelihood) levels as well as at higher-progress (lower likelihood) levels – “progress” being judged neutrally whether boosted by higher levels of funding, effort or innovation, slowed by lower general investment, or halted by known or unforeseen physical or regulatory boundaries. As Annex D indicates, the rates of aerodynamic drag reduction potential reduce for later decades. The aerodynamic technologies considered have a finite maximum practical and certifiable increment, and, as a result, the relative technology increments will inevitably reduce over time.

The key geometric parameter that drives induced drag reduction opportunity is wing span. The selection of wing span (or aspect ratio) is a key result of extensive MDO type integration and optimization – composite materials and load alleviation can allow increased wing aspect ratio, whilst minimizing wing structural weight. The MDO preliminary design process done as part of current LTAG study by Georgia Tech M&S team accounts for wing span and wing weight trades within specified wing aspect ratio constraints. The assumed wing aspect-ratio constraints are different for the various TRA configurations (Annex E in this LTAG report).

Once the above considerations of key viscous and induced drag potential had been quantified, a further (modest) drag improvement potential was added for each of the TRAs, with the assumptions based on how effectively the various technologies – new and existing – might be combined, integrated and optimized into further drag improvement through multidisciplinary analysis and optimization processes (MDAO). For the purposes of the Georgia Tech modelling activity, this opportunity was bundled within the viscous-drag increments.

4.3 AIRFRAME STRUCTURE MASS REDUCTION OPPORTUNITIES (AIRFRAME TAHG)

The reduction of the structural mass of the aircraft is a key parameter that can improve its fuel burn performance. This structural performance can be generated by several means:

- Better use of technologies /materials (including relaxing conservatism linked to requirements, optimization and multifunctional approach due to improved design and verification methods)
- Introduction of new materials and or technologies

- New aircraft architecture (not included in the TRA technologies summarized in Appendix D – which considers only wing and tube structural architecture opportunities)

It is important to highlight some interdependencies with other topics where weight penalties can be identified (e.g. higher aspect-ratio wings with increased end loads, or increased nacelle diameter for engine efficiency). The savings identified as Airframe structure weight reduction are not considering potential interdependencies and are only quantified for the TRA-type aircraft configurations.

The structural layout of the reference aircraft configurations is key to evaluate potential improvements: The large single-aisle aircraft, such as A320neo and B737MAX, and long-range twin-aisle B777 and A330 have mostly metallic primary structures. The twin-aisle B787 and A350 have mostly composite primary structures - limiting the potential for further significant benefits from composite technologies.

The airframe structures were split into four major groupings: wing, fuselage, empennage and nacelles (importance of the reference Aircraft configuration and technologies). The technologies included in the review are related to these groupings and do not include the mass of associated items such as systems and equipment installed within the structural groups. Landing gear was treated as a “Systems” item and was not considered. Within the airframe structures topic, mass-saving opportunities obtained by the use of advances in the following areas were considered:

- Lightweight technologies
- Multifunctional optimized design
- Shape control
- Nacelle improvements

The structural / materials advances described hereafter are aligned with the benefits identified in Annex D technology tables for the various TRA classes.

4.3.1 Lightweight technologies

The structure technologies and material are still evolving enabling weight savings. Two main families can be defined: composite and metal options. The significant use of composite-materials on modern commercial long-range aircraft can be further improved with new performance materials associated with new joining technologies like welding (for thermoplastics resins), bonding and stitching. For metallic technologies, some low-density alloys with improved strength can be used with improved joining technologies like welding and bonding. The choice of the technology is mainly linked to the aircraft loading and environment with a clear push towards empennage and wing composite solutions (see Figure 4-5, image courtesy of Airbus [9]). The challenges inherent to composite materials on system installation (linked to composite electrical property with strong interdependencies on systems assumptions) is an important consideration for incorporation of composite-materials to fuselages for non-long-range aircraft.

Figure 4-5. Composite Upper Wing Skin with Composite Stiffeners (Wide-Body Aircraft)

4.3.2 Multifunctional and optimized design

Another way to achieve additional weight savings is via integrated design that allows further optimization as well as incorporates further multifunctional opportunities (these two items can be combined via multifunctional optimization). In this case, new technologies such as additive-layer manufacturing methods and bionic structural concepts (see Figure 4-6, image courtesy of Airbus [9]) can permit design solutions and opportunities not possible with legacy methods and technologies. Materials and structural design and optimization are now more efficient thanks to greatly improved computational simulation methods. Finally, integration of additional functionality in the structure can allow better integrated weight performance. The multifunctional approach can be done at the materials level (e.g. damping, thermal insulation, surface treatments, electrical properties) or at the part and component level (system/structure functionality).

4.3.3 Shape control

On the wing, it is possible to reduce the loads by having a load alleviation approach. This can be an active or passive alleviation. Advanced load alleviation is an example of favorable interaction between aerodynamics and wing structural design. Further wing-span increases without significant concomitant weight increase are facilitated by introduction of reliable load-alleviation systems. The active alleviation solution is accomplished by moving wing-mounted control surfaces such as ailerons and spoilers using suitable sensor and control parameters towards limiting wing root bending moment. This effect can be done passively by means of flexible wing and wing tips with a highly swept planform. Suitable design of composite structure can contribute to passive load alleviation via optimized fiber lay-up [9]. The effect on weight will be through reduction of sizing loads without impacting aircraft structural safety. Load alleviation is already introduced on some of the existing TRA aircraft at various degrees – resulting in different opportunities for different aircraft classes.

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9 ICAO 2019 Environmental Report (Chapter 4 - Climate Change Mitigation: Technology and Operations) https://www.icao.int/environmental-protection/Pages/envrep2019.aspx)

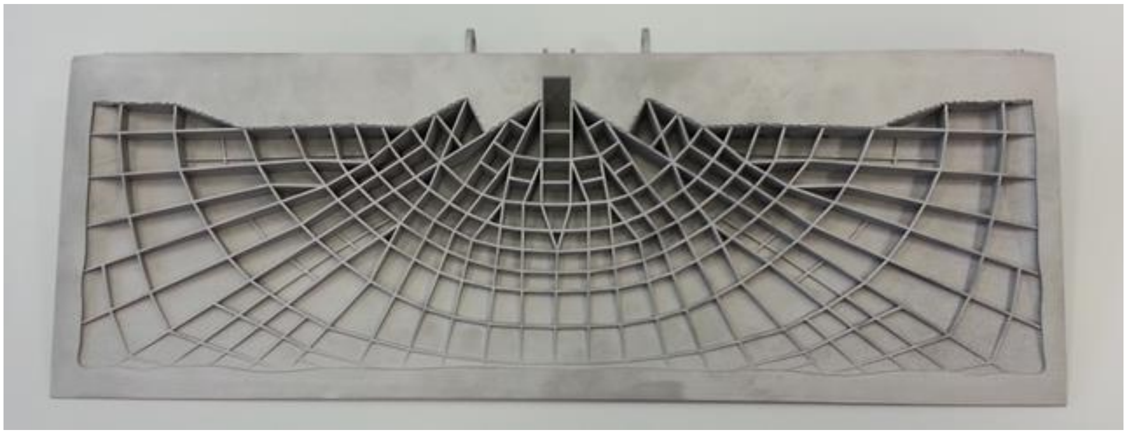


Figure 4-6. Additive-Layer Manufacturing "Bionic" Type Structural Optimization in Wing Spoiler Component

4.3.4 Nacelle improvements

Concerning nacelles, introduction of new designs and component technologies can generate weight savings. The structural improvement will be coupled to more efficient acoustic approach enabling the overall performance. In addition to progressive increase in use of lighter materials, potential reduction in inlet length towards more compact nacelles can result in net nacelle weight reduction. Furthermore, additional structural and materials optimization and enhancement in nacelle thrust-reverser systems, and nacelle-pylon configuration integration can enable additional nacelle weight improvements.

4.4 AIRFRAME SYSTEMS REDUCTION TECHNOLOGIES (AIRFRAME TAHG)

Improvements in systems design are also key to achieving future aircraft CO_2 reduction goals. It is essential to emphasize the increasing importance of systems integration in aircraft design. Some of the technology opportunities discussed in Sections 4.2 and 4.3, such as fuel burn reduction due to wing structure weight decrease or increased span, are subject to the key interaction between mechanical systems (actuators, hydraulics, and electrical components) coupled with flight control computers and sensors to enable advanced loads control.

In addition, several technology improvements are being progressed towards possible practical application for systems. These technology applicability and maturation potentials are different for the various aircraft TRA classes. This section summarizes the key aspects considered in Annex D for airframe systems technologies.

4.4.1 Engine Power Extraction

Potential improvement increases as aircraft replace hydraulic and pneumatic systems are replaced with (more) electrical equivalents. As large engine BPRs have increased up to 10+, with small, high speed, high temperature cores, the impact of an air bleed for all services has become more significant, in terms of SFC. Shifting to electric offtakes for the aircraft environmental control and ice-protection systems comes out more attractive for SFC, but raises new challenges such as engine compressor operability. The SFC improvement is traded against the weight impact due to the increased capacity of electrical generators and electrical distribution system compared to a pneumatic one considering a typical mission for a given TRA.

One version of this technology is in-service on the Boeing B787 (but was not adopted in the Airbus A350). It has not reached TRL9 for single-aisle, regional airplanes, turbo-props or business jets. Such a significant architecture change compared to a conventional solution is not likely to happen on a derived version. Nevertheless, future clean-sheet designs for NB, RJ and TP configurations that utilize propulsion systems with increasingly limited bleed-air availability might adopt this new architecture if the technology sufficiently matures.

4.4.2 Cabin Environmental Control - Adaptive ECS (Filtration and Reconfiguration)

All the contemplated improvement here is subject to current Part 25.831 certification requirement changes from 0.55 parts per million of fresh air per occupant plus maximum CO_2 and CO concentrations, to only retaining the latter requirement on maximum CO_2 and CO concentrations. The existing technology components for air quality sensing and air treatment could be adapted in order to reduce the amount of air bled from the engines whereas still addressing cabin pressurization demand and resulting in some SFC benefit. However, reduced cooling performance delivered by a smaller pack would have to be compensated by additional ram air which would mean a drag increase partially offsetting the SFC improvement benefit. The net fuel burn improvement is deemed as 0.5% ± 0.25%. As this improvement is subject to certification requirement change, the SFC benefit was considered for all TRA only in 2050. The adaptive ECS (Environmental Control System) benefit is not additive to the one achieved in transforming pneumatic bleed extraction into mechanical/electrical power extraction:

- A reduction of the cost of this power extraction will naturally lead to a reduced benefit if further reducing the airplane pack flow.
- An electric compressor feeding the air conditioning pack will always provide air with a pressure closer to the minimum required pressure than an engine bleed port. Thus, the pack cooling performance (per the airflow expansion) will be lower in the case of an electric compressor and will require a greater cooling demand for adaptive ECS. Any additional ram air need would again reduce the benefit of reduced pack flow.

To sum up, the drag increases due to additional ram air that needs to be accounted for in order to assess the net benefit is greater when combining adaptive ECS and switching from pneumatic bleed to mechanical/electrical power extraction.

4.5 PROPULSION FUEL BURN REDUCTION TECHNOLOGIES (PROPULSION TAHG)

A Propulsion Tahg was formed to consider a range of technologies as part of its assessment of existing, foreseen and innovative concepts that could reduce the contribution of the propulsion system to future aircraft's CO_2 emissions. The Propulsion Tahg included 39 individuals with diverse backgrounds and globally distributed from a variety of academic, governmental and industry entities. Work within the Tahg supported the determination of impacts of future propulsion systems on both ATW and ACA vehicles for the LTAG analysis. For reference, a configuration summary of a modern state of the art commercial propulsion system is provided in Figure 4-7.

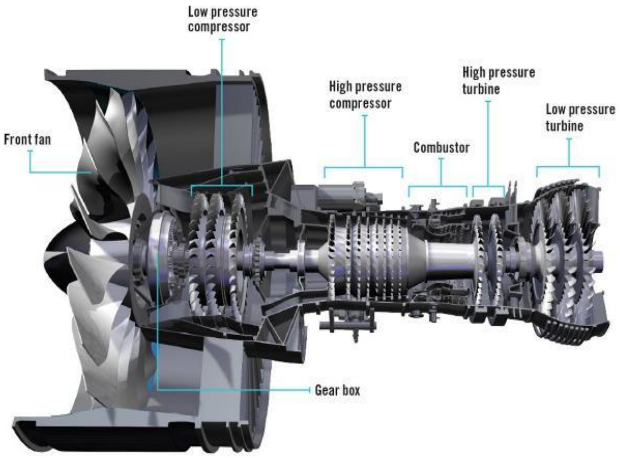


Figure 4-7. Modern commercial engine outlining a Geared Turbofan Configuration (image credit: Pratt & Whitney)

In order to support the assessment of the ATW vehicles, the Tahg met to compare perspectives on the readiness, attainability, and feasibility of future technologies. In support of LTAG modeling and analysis objectives, the Tahg considered how those technologies would impact key propulsion design and performance parameters in future aircraft. This included a literature review and data gathering process during which Tahg members brought forward academic papers covering technologies relevant to the effort.

The Tahg agreed that the propulsion impacts from the 2019 IEIR study would be used as a format for documenting technology impacts. The 2019 IEIR inputs were used as an initial set of values and updates were made based upon recent developments, new findings, and input from ICAO Stocktaking events and Tahg members. A sub-team of ICCAIA industry experts met to formulate initial updates for the propulsion technology impacts for each aircraft class in 2030 and 2040, as well as generating new impacts for 2050, and brought those results back to the larger Tahg for review and approval. Turboprop (TP) propulsion systems were not part of the 2019 IEIR effort and the IEIR parameter set was found to be unsuitable for TP configurations. Therefore, a sub-team of propulsion system experts was formed to work with the M&S Tahg to identify parameters suited to TP applications and create propulsion impacts at the required time horizons.

The Propulsion Tahg outputs represent the potential changes in propulsion system capabilities for each category of aircraft. The LTAG M&S team used the new ranges of technological capabilities to perform aircraft level optimization and provided detailed outputs on the propulsion systems selected for each category of aircraft so that the Propulsion Tahg could review the integrated results and update as needed (see Figure 4-8).

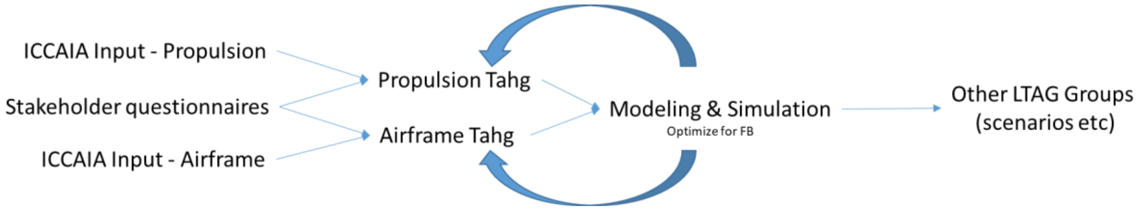


Figure 4-8. Flow of Information from Subject Matter Experts to Modeling & Simulation

Details of the M&S Tahg’s modeling and analysis process and use of the provided capability levels (i.e. impacts) are documented in Section 5.2. Once the ATW iterations with M&S were completed the

Propulsion Tahg held a formal review meeting to allow all members of the Tahg to ask questions, raise concerns and provide feedback. At the conclusion of the formal review, the Propulsion Tahg unanimously concurred that:

- *The M&S results adequately captured the Propulsion System Technologies and are Fit for Purpose In the LTAG Modeling Process*
- *The M&S process was logical, reasonable and appropriately implemented Propulsion Tahg inputs for key parameters:*
    - *Fan pressure ratio (not directly applicable for turboprops)*
    - *Core weight reduction*
    - *Propulsor weight reduction*
    - *Overall pressure ratio (OPR)*
- *The Propulsion Tahg recommended "small core efficiency improvement" (size effects) levels are similar to IEIR modelers values and appear to have been transferred appropriately*
- *The optimal aircraft solutions identified by the M&S Tahg are reasonable and within Propulsion capabilities defined by Propulsion Tahg.*

Upon completion of the inputs for the ATW vehicles, the Propulsion Tahg engaged with the ACES Tahg to capture the impacts of propulsion systems on ACA vehicles. The process for ACAs is necessarily more complex given the wide variety of potential ACAs, many of which change conventional technical trade decisions and integration approaches. Given this complexity, the LTAG agreed to consider propulsion and airframe ACA technologies as combined entities – distinct propulsion technologies/trends and their related fuel burn impacts were not assessed. For example, Boundary Layer Ingestion configurations require complete integration of the propulsion system into the airframe to successfully deliver the aircraft boundary layer in the propulsor while the fan must be designed to deal with high levels of flow distortion (circumferential, radial and swirl) without compromising structural integrity and fan efficiency. More information on how the ACA vehicles' propulsion impacts were captured by the Propulsion Tahg and ACES effort is covered in section 4.5.5. The following five sections will focus on Propulsion Tahg results in more detail - summarizing the ATW propulsion trends assessment process, key engine design/efficiency improvement elements, weight reduction technology trends, and interdependencies between CO_2 (fuel burn) reduction and other propulsion/airframe figures of merit.

4.5.1 Integration with the LTAG Technology Assessment Process & Key Parameters

One of the first tasks of the Propulsion Tahg was to align – or "bucketize" – classes of propulsion system technologies consistent with the LTAG technology modeling process. As shown in Figure 4-9 below, the Propulsion Tahg chose 3 buckets: conventional technology, un-conventional technology contained within the engine control volume, and un-conventional technology requiring airframe changes.

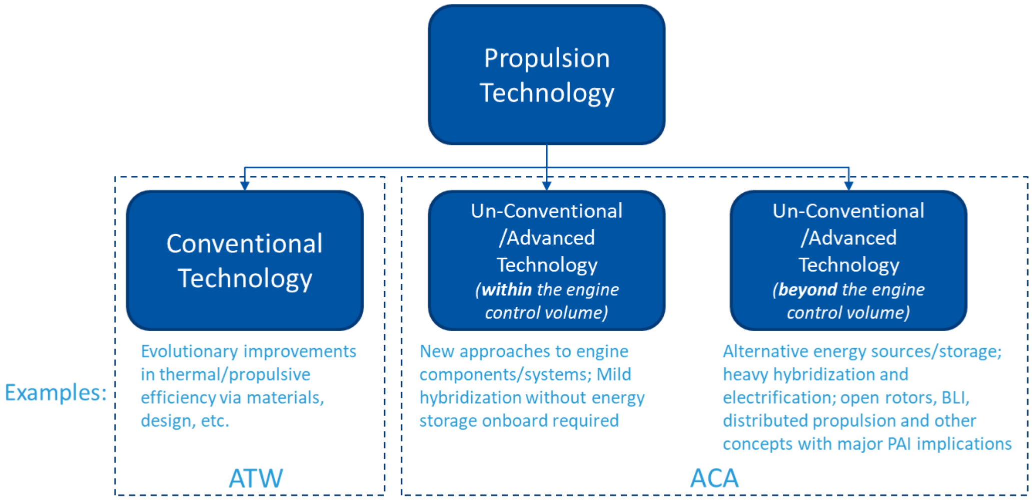


Figure 4-9. Propulsion Tahg Technology Buckets

4.5.2 Propulsion Technology Buckets

For purposes of ATW detailed modeling, only the conventional technology bucket was considered. The two unconventional technology buckets were considered as part of the ACA assessment process. Most of the content covered in the remainder of the propulsion section addresses the ATW technology trends/modeling activity. Discussion of the propulsion inputs to the ACA assessment process are discussed in Section 4.5.6.

The following sections cover the key propulsion parameters that drive energy efficiency and thereby CO_2 emissions for aircraft, and discuss the relevant technologies and impacts determined by the Propulsion Tahg. The contributions of a propulsion system to the aircraft's overall energy efficiency can be captured in terms of the thermal efficiency, propulsive efficiency, and the weight of the engine, as well as its contribution to aircraft drag. This approach and propulsion parameters were selected after discussions with the M&S Tahg. It allows the potential changes in system level physical capabilities of the propulsion system to be modeled and optimized at the aircraft level while avoiding the complexity of modeling the wide variety of features that make up a propulsion system with the conventional Brayton thermodynamic cycle employed by gas turbines. It should be noted that the final level selected for each aircraft and time horizon was defined by the M&S Tahg (see Figure 4-8) and represents the best overall aircraft solution and may not necessarily align with the maximum values specified by the Propulsion Tahg. The Propulsion Tahg decided to capture the three main areas of contribution of the propulsion system to the overall aircraft's performance using five parameters at key operating conditions (Aero Design Point = ADP, Max Climb = MCL and MCR = Max Cruise Condition):

- Thermal Efficiency
  - Overall engine pressure ratio (at MCL)
  - Small core efficiency improvements (relative to TRA, MCR)
- Propulsive Efficiency
  - Fan pressure ratio (at MCR) / Propeller Efficiency for TP
- Weight
  - Core component weight reduction (relative to TRA)
  - Propulsor weight reduction (relative to TRA)

The Propulsion Tahg tackled the parameters associated with the engine itself, rather than its installation aspects (nacelle weight and drag impacts), which were handled by the Airframe Tahg. Full documentation of the propulsion impacts provided by the Propulsion Tahg to the M&S Tahg for each aircraft class are documented in Annex C.

4.5.3 Improved Thermal Efficiency

Throughout the course of history of gas turbine development, designers have sought to increase thermal efficiency by increasing OPR of the engine, increasing turbine inlet temperature (TIT), improving turbomachinery component efficiencies, and reducing turbine cooling. These changes have been enabled by the development of materials capable of routinely withstanding temperatures of 1,000K, turbomachinery that is well over 90% efficient, and cooling schemes, materials and coatings that enable turbines to operate safely at 2,000K for many thousands of hours. However, the rate of improvement in materials, cooling and efficiency has reduced over time. Additionally, with the conventional Brayton physical cycle employed by gas turbines the fuel burn improvement for a given improvement in OPR or TIT is reaching asymptote as the cycle reaches the theoretical limit. With the current state of the thermal efficiency at around typically 50-53%, it is becoming progressively more difficult to improve thermal efficiency. A further factor in improving thermal efficiency is the balance between engine Time on Wing, a key factor in maintenance cost and operating economics, versus improved fuel burn through thermal efficiency which will increase operating temperatures. Gas turbines are necessarily optimized to operate at the highest feasible temperatures and most materials rapidly deteriorate if operated at higher temperatures, resulting in shorter component lives and substantially higher maintenance costs which are not offset by the modest improvement in fuel burn.

Relative to a 2018 TRA, 8-12% improvement in small core thermal efficiency improvement is possible by 2030, with 10-19% by 2040 and 10-25% by 2050, ranging from low to high progress scenarios. Engine overall pressure ratio at MCL is foreseen to increase by 6-58% by 2050 for the lower progress scenarios and from 30-88% for the higher progress scenarios compared to the 2018 TRA. The level of improvement varies drastically within each progress scenario depending upon aircraft and engine size class. The trend of OPR vs. Entry into Service (EIS) timing provided by the Propulsion Tahg for widebody market aircraft is shown in Figure 4-10 below. Inputs were provided for high, nominal, and low probabilities of realization by the given EIS year.

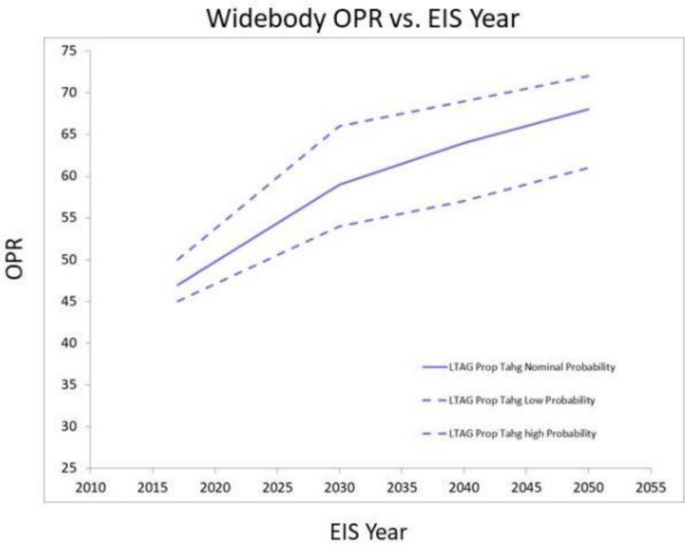
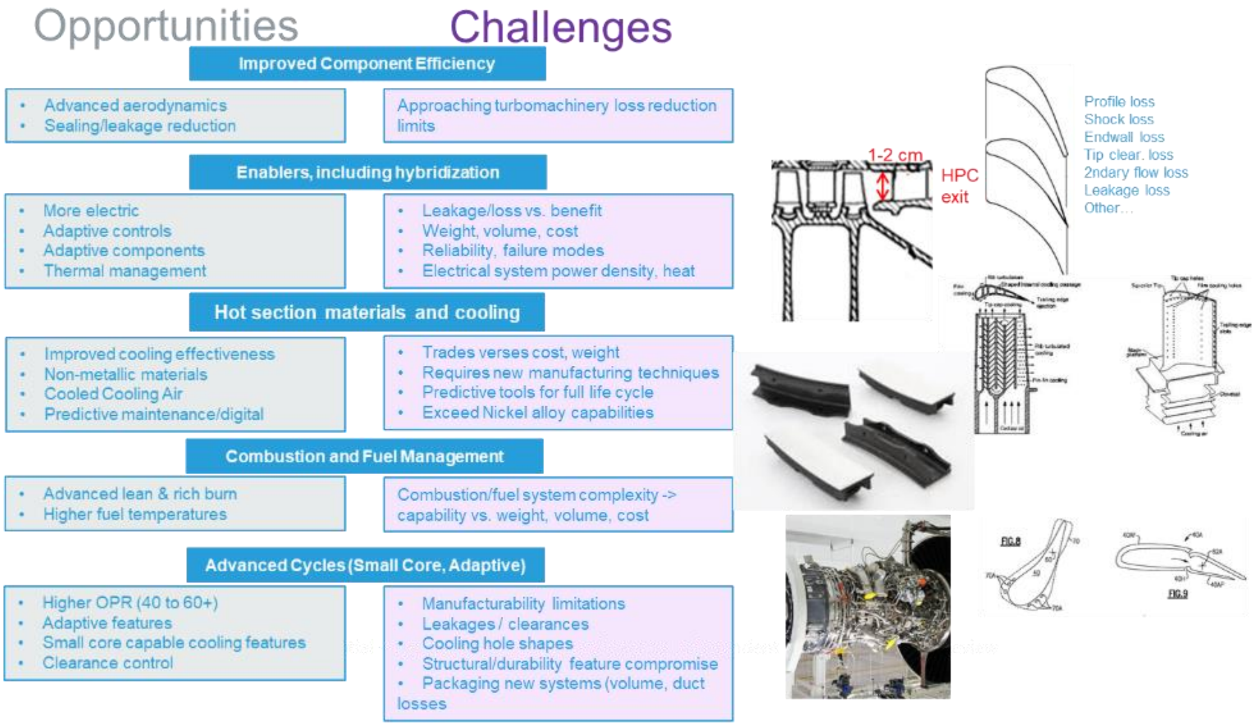


Figure 4-10. Widebody OPR vs. EIS Year

The largest OPRs, as expected, are possible for widebody aircraft with the largest engines, as high as 61-72 by 2050 because of the relatively lower portion of the mission at high temperature conditions such as take-off and climb and relatively higher fraction of the mission at high altitude cruise conditions which are cooler. Additionally, WB aircraft consume a large absolute volume of fuel meaning that a given percentage improvement is substantially more valuable than in other classes. Amongst the RJ, NB and WB aircraft classes, the future versions of the larger aircraft are projected to achieve larger relative gains in OPR when compared with their TRA aircraft. The TP and BJ aircraft classes are also foreseen to achieve even larger relative gains in OPR compared to their TRA aircraft, as additional technologies are applied to these smaller engines. The economic feasibility of applying these technologies to TP, BJ and RJ aircraft is unclear because while the percentage reduction in fuel burn is similar to other classes the absolute reduction in fuel is substantially lower.

Increases in thermal efficiency through increased OPR and TIT will require turbomachinery technologies that mitigate current inefficiencies and challenges with high temperature turbine operation and cooling. The thermal efficiency opportunities and challenges are depicted in Figure 4-11. The Propulsion Tahg noted that these challenges can be grouped into three main categories:

- Improved component efficiencies, including enablers such as hybridization
- Hot section materials & combustion technologies to minimise parasitic cooling air losses at higher compressor delivery temps with commercially acceptable durability
- Small core enabler technologies; improved cooling schemes, tip clearance management and scaling of key physical features



Opportunities	Challenges
Improved Component Efficiency	
• Advanced aerodynamics • Sealing/leakage reduction	Approaching turbomachinery loss reduction limits
Enablers, including hybridization	
• More electric • Adaptive controls • Adaptive components • Thermal management	• Leakage/loss vs. benefit • Weight, volume, cost • Reliability, failure modes • Electrical system power density, heat
Hot section materials and cooling	
• Improved cooling effectiveness • Non-metallic materials • Cooled Cooling Air • Predictive maintenance/digital	• Trades verses cost, weight • Requires new manufacturing techniques • Predictive tools for full life cycle • Exceed Nickel alloy capabilities
Combustion and Fuel Management	
• Advanced lean & rich burn • Higher fuel temperatures	Combustion/fuel system complexity -> capability vs. weight, volume, cost
Advanced Cycles (Small Core, Adaptive)	
• Higher OPR (40 to 60+) • Adaptive features • Small core capable cooling features • Clearance control	• Manufacturability limitations • Leakages / clearances • Cooling hole shapes • Structural/durability feature compromise • Packaging new systems (volume, duct losses

Figure 4-11. Thermal efficiency technology opportunities and associated challenges

The (adiabatic) efficiencies of the gas turbine turbomachinery (i.e. fan, compressor and turbine) are already very high given extensive development over many decades. At constant turbomachinery size, there is certainly some further gain to be obtained, although the improvement rate is likely to be substantially lower than has been the case in the past. As an example, several academic studies have defined 95% polytropic efficiency as the theoretical limit for axial compressors, representing a highly idealized configuration such as zero thickness airfoils, ideal surface finish, ideal clearances and no leakage. Current world class large WB compressors are in the 91-92% efficiency range. Therefore, achieving a 1% compressor efficiency improvement, resulting in 0.6-0.7% fuel burn reduction would require a 25% reduction in the loss between current state-of-the-art and ideal theoretical performance. Over the long-term, it is viewed that the polytropic efficiency of the compression system might be improved by ~1-2% beyond the current state-of-the-art through the application of advanced aerodynamic design methods, clearance management, sealing and potentially new aerodynamic design space selection to trade cost for performance.

Increasing turbine inlet temperatures and/or reducing cooling flows required to provide commercially acceptable durability has a direct beneficial impact on thermal efficiency. Extensive research, and many technological breakthroughs, over many decades has resulted in nickel superalloys, cooling schemes, materials and enhanced coatings enable turbines to survive at 2000K for many thousands of flight cycles. However, current research on superalloys indicates that no further radical improvements are to be expected. The current development in temperature capability seems to be levelling out and designers now face having to trade one property for another.

The focus for higher capability materials has shifted from nickel-based superalloys to other potential solutions. These new materials offer the potential for higher temperature capability but pose different challenges such as structural capability limitations, lower resistance to environmental pollutants and significantly different mechanical properties to surrounding hardware. Ceramic matrix composites (CMC) are expected to be progressively introduced into ever hotter parts of the combustor and turbine system. Long-term, it is feasible to have HPT parts including the nozzle and, ultimately, possibly turbine blades manufactured using CMCs. There are also new hot-section materials like eutectic ceramics and intermetallic alloys which may be able to operate at higher temperature than superalloys currently in use. These new materials do not appear to be readily applicable to rotating components such as disks, and therefore sealing and cooling technologies will be required for these components to enable higher gas path temperatures, although this is considered significantly less challenging than maturing the new material systems.

It is expected that the design of HPT airfoils will continue to be refined, including the high thermal effectiveness cooling circuits inside blades and vanes, albeit with ever decreasing returns on temperature capability, reduction in cooling mass flow requirement, and efficiency penalties. Similar evolutionary progress is expected in the areas of thermal barrier coatings. A less conventional way to improve temperature capability is to use novel means for heat management. The introduction of variability in the cooling flow to adjust to the flight envelope requirements is expected.

The high-pressure compressor (HPC) exit is also becoming very hot relative to material capabilities, but suitable and promising new materials are not evident. Additionally, the increase in OPR reduces the size of the last stages of the high-pressure compressor to a degree that the achievable compressor efficiency starts to drop. This reduction is driven by relative increases in tip-clearances, reduction of Reynolds number, small-size manufacturing imperfections and end-wall boundary layer interaction.

A consequence of higher efficiency, lighter weight aircraft is that less thrust is required. At the same time more efficient, higher OPR concepts result in smaller, hotter turbomachinery. Based on these trends, turbomachinery will be required to scale down to new design spaces below conventional axial turbomachinery experience. In this design space, the compressor outlet and HPT turbine blade heights are small in relation to diameter, and this makes it particularly difficult to achieve high efficiencies and maintain high performance cooling systems. Here, tip clearance management, leakage management, and high temperature materials are key enablers. Without new technologies and techniques, the detrimental impact of scaling down on efficiency and cooling requirements will offset any potential benefit from OPR and T41 increases.

A wide variety of possible technologies exist, including aerodynamic technologies to desensitize the design to clearances, leakages and variation, manufacturing technologies to enable highly repeatable precision manufacturing, materials to deliver additional structural capability, and mechanical concepts to mitigate clearances, leakages and structural responses. These challenges are most acute in the SA and smaller classes due to the smaller scale of turbomachinery required. The Propulsion Tahg chose to capture these future "small core efficiency" technologies as a reduction in the loss incurred by small core turbomachinery. n the M&S propulsion system modeling process, this loss reduction was used to modify (reduce) a base core loss curve applied as a function of core size (airflow). The table of Propulsion impacts for small core efficiency loss reduction implemented by the M&S Tahg is listed in Table 4-1 below. As an example, a narrow body engine small core with a base curve loss of 20% for size effects would have that loss reduced by 17% in 2040 (medium progress scenario). This 17% loss reduction would result in a new small core loss of 16.6%, and a corresponding improvement in core component efficiency.

Table 4-1: Small Core (Size Effects) Loss Reduction as a Function of EIS Date

		2018	2030	2040	2050
		2010 TRL6	2023 TRL6	2033 TRL6	2043 TRL6
WB	High Confidence	BASE	8%	14%	20%
	Med Confidence	BASE	10%	17%	23%
	Low Confidence	BASE	12%	19%	25%
NB	High Confidence	BASE	8%	14%	20%
	Med Confidence	BASE	10%	17%	23%
	Low Confidence	BASE	12%	19%	25%
RJ	High Confidence	BASE	8%	14%	20%
	Med Confidence	BASE	10%	17%	23%
	Low Confidence	BASE	12%	19%	25%
BJ	High Confidence	BASE	8%	12%	13%
	Med Confidence	BASE	10%	12%	14%
	Low Confidence	BASE	12%	12%	15%
TP	High Confidence	BASE	8%	10%	10%
	Med Confidence	BASE	10%	12.5%	15%
	Low Confidence	BASE	12%	15.0%	20%

This section and inputs to the M&S Tahg focused on conventional turbomachinery. Other, less conventional, concepts for improving thermal efficiency exist such as water cooling, intercooling and electrical hybridization. These concepts were treated as part of advanced concepts work due to the higher level of interdependency with the airframe configuration through increased weight or drag. It is important to note that modern turbomachinery is trending towards lower specific thrust to achieve improved propulsive efficiency. This design selection optimizes overall fuel burn but results in higher core temperatures across the whole flight envelope, indeed the top of climb condition is close to replacing take-off as the most challenging operating point. This change means that technologies to improve thermal efficiency must be capable of sustained operation across a large portion of the flight envelope.

Thermal efficiency has a direct impact on fuel efficiency. Design parameters for thermal efficiency can also strongly influence non-CO_2 emissions. A relevant example is the correlation between higher T3 and higher NO_x generation. These dependencies are noted in the Dependencies section below. The thermal efficiencies computed by the M&S Tahg's analysis efforts for each ATW aircraft class, development level, and timeframe are illustrated below for the aerodynamic design point conditions. In Figure 4-12, each solid line represents the medium progress scenario for an aircraft class, while the dotted lines represent the lower and higher bounds of progress for each aircraft class.

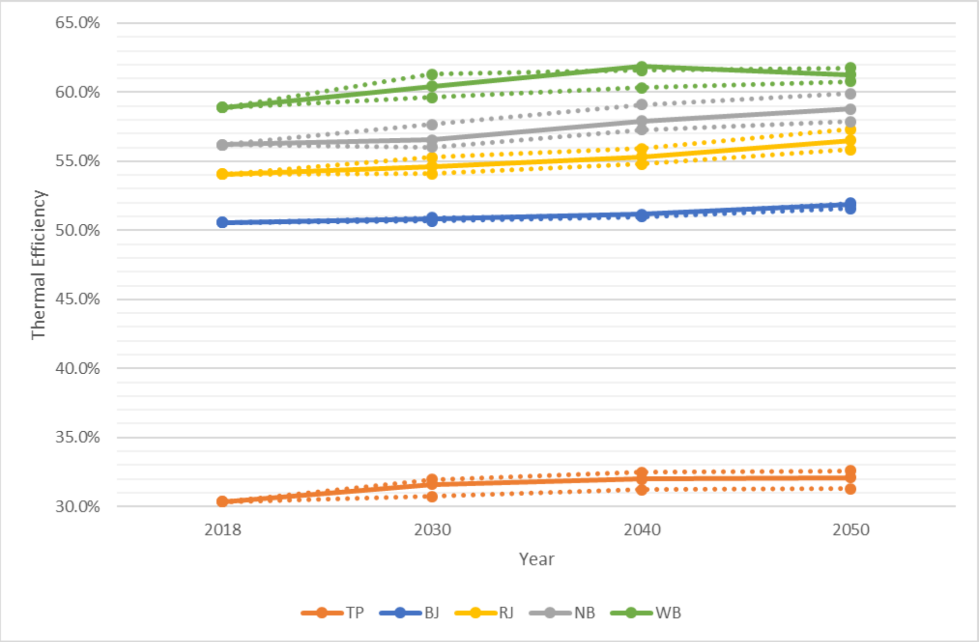


Figure 4-12. Thermal Efficiencies at Aero Design Point - Output by M&S Process

4.5.4 Improved Propulsive Efficiency

Improvements in propulsive efficiency are the result of lowering FPR and increasing BPR, reducing jet velocity and increasing the overall mass of air being moved by the engine's fan. While this improves overall efficiency of the engine, it drives increases in engine diameter (notional depiction in Figure 4-13, thereby increasing the weight of a range of propulsor components, increasing nacelle drag, and introducing installation constraints as fan diameters increase.

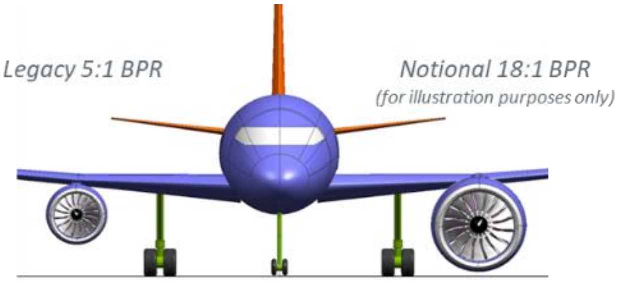


Figure 4-13. Comparison of Legacy and Notional Ultra-High Bypass Ratio Engine Sizes

The optimization of the engine and airframe integration is a complex undertaking across the airframe and engine manufacturers. The optimal customer value depends significantly on aircraft level trades, technology assumptions and balancing these effects against the desired mission. Examples of some of the trades are provided in table Table 4-2. To support M&S ATW modeling, the propulsion Tahg provided potential future engine FPR vs. EIS timing trends. An example for widebody (twin aisle) aircraft is shown in Figure 4-14.

Table 4-2: Example Airframe and Engine Integration Trades

Effect	Examples
Airframe structure	Landing gear length, wing planform, additional structure
Propulsion system weight	Engine, nacelle, pylon
Cost	Larger/heavier components, landing fees
Installation effects	Wing interference

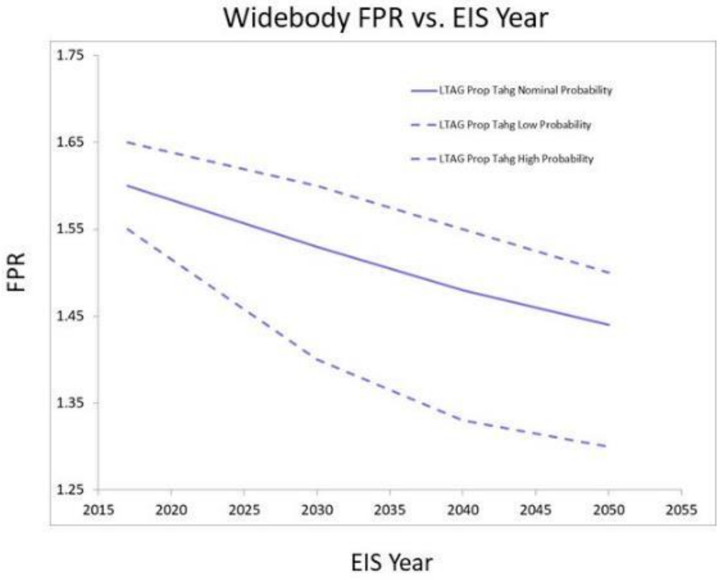


Figure 4-14. Wide Body FPR vs. EIS Year Projected Tren

By 2050, fan pressure ratios at MCR may be reduced by between 5 and 11% for lower progress scenarios and by between 7 and 19% for higher progress scenarios. The lowest fan pressure ratios are expected for NB and WB aircraft, at 1.3 in the highest progress scenario by 2050.

These low-speed fans will need to be accompanied by advanced nacelle technologies and design methods that allow thinning and shortening the nacelles. In turn, this will demand more complex optimization for the propulsor including combined aerodynamics and acoustics considerations. Shortening nacelles will limit noise shielding and use of acoustic liners; it will also make the fan more vulnerable to cross-wind distortion or the distortion at angle of attack, so that the fan and nacelle integration become more challenging. Design methods will be required that include the intake, the fan and the full by-pass duct taking multidisciplinary considerations into account.

The reduction in FPR produces larger and heavier engines with greater interaction with the airframe. The fan is now the largest noise source for take-off, but the potential mass of the intake and nacelle tends to make these shorter with an adverse impact on noise. All this requires greater use of multidisciplinary engine design, but going beyond this requires strengthened co-engineering between aircraft integrators to include aircraft, engine and nacelle manufacturers. Improved hollow metallic and composite fan blades, containment systems and other advanced concepts for mass reduction will play a key role to enable future ultra-efficient and ultra-low FPR designs. It is expected that improved integration of the whole power plant with the wing may still bring benefits. For very large fan diameter installations, even the overall structural concept to hold the engine under the wing may need revisiting, or a switch to a high wing may become necessary.

At the start of take-off, with low forward speed, low FPR fans are susceptible to flutter or are prone to stall and surge. Until now, this problem was managed by including margin in the aero-design, perhaps with a small penalty on performance at cruise conditions. As FPR is lowered further, it is expected that a condition will be reached at which this no longer provides an acceptable installation and new technologies will be required. Potential technologies include variable area nozzles or variable pitch fans, however, substantial advancements in mass reduction, cost reduction and reliability beyond the current state-of-the-art are needed for these technologies to become attractive.

This section and inputs to the M&S Tahg focused on conventional turbomachinery. Other, less conventional, concepts for improving propulsive efficiency exist such as Boundary Layer Ingestion or Distributed Propulsion. These concepts were treated as part of advanced concepts work due to the higher level of interdependency with the airframe and the low level of TRL. Additional information is provided in the Advanced Concepts section below and the ACES Tahg sections.

The propulsive efficiencies computed by the M&S Tahg for each aircraft class, development level, and timeframe are illustrated below for the aerodynamic design point conditions. In Figure 4-15, each solid line represents the medium progress scenario for an aircraft class, while the dotted lines represent the lower and higher bounds of progress for each aircraft class.

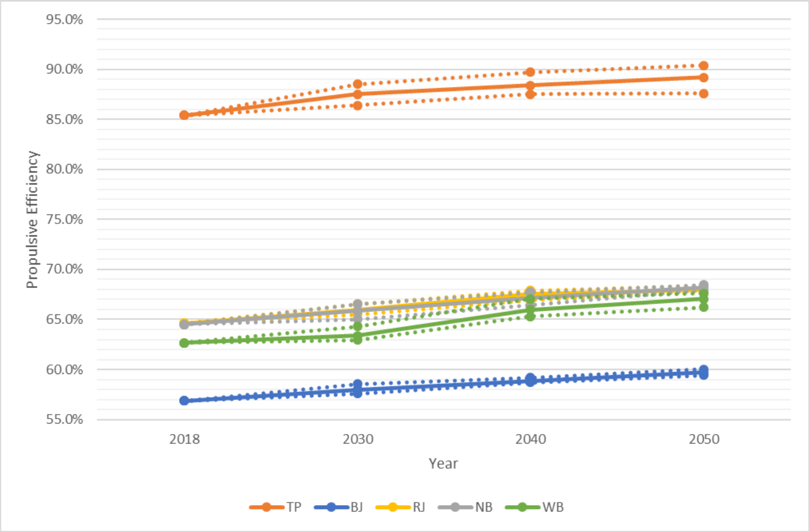


Figure 4-15. Propulsive Efficiencies at Aero Design Point - Output by M&S Process

4.5.5 Component Weight Reduction

Propulsion system weight has typically been a second order effect on fuel burn compared to thrust specific fuel consumption (TSFC) and other integration effects. Many technologies implemented to achieve the large historical improvement in fuel burn, for example turbofans and then high By-Pass Ratio (BPR) engines, have resulted in relatively heavier configurations, and weight reduction technologies have been "spent" to minimize the negative weight impact of the configuration changes. This has resulted in a flattening of the Thrust-to-Weight (T/W) ratio of commercial engines as seen in Figure 4-16. The variation in T/W is due to two primary factors: (i) the thrust class of the engine, with larger engines being relatively more weight efficient because many components do not scale down (e.g. controls and externals) and (ii) other requirements not represented in this simple plot such as thrust demands elsewhere in the flight envelope.

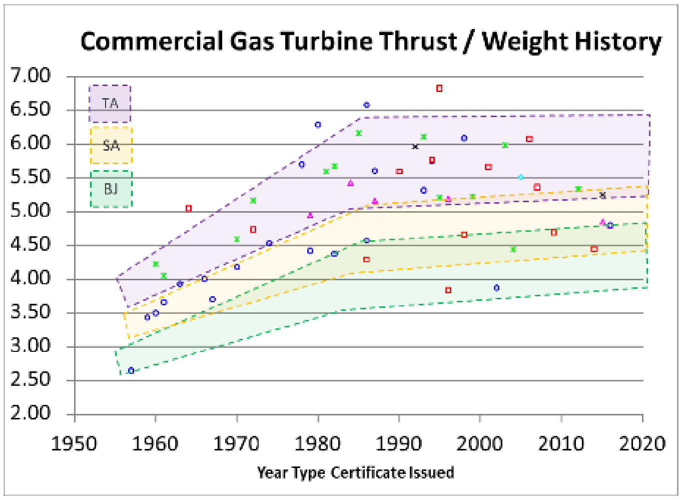


Figure 4-16. Commercial Gas Turbine Thrust / Weight History

The majority of engine weight reduction historically has come from material and manufacturing technology advancements such as advanced titanium alloys or organic matrix composites. Continued engine weight reduction is possible as engines are developed over the coming decades. Many weight reduction efforts will be focused on the propulsor in order to offset the effects of lower fan pressure ratios and higher bypass ratios on engine diameter and thereby enable greater propulsive efficiency. In modern engines the fan module may constitute 15-20% of the overall engine mass and is therefore a natural focus area. Reducing engine core size, made possible by advancements in aerodynamic design and manufacturing technologies, may help to minimize weight growth as fan pressure ratio is decreased. However, there is also room for continued improvement in component weights in other areas of the engine.

This is expected to result from continued expansion of new materials and their applications. Polymer matrix composites have already brought significant weight reduction to some engine components, and improved manufacturing processes are expected to improve the properties of these materials and drive down cost to enable application to additional engine components. Ceramic matrix composites, as mentioned previously in the discussion of their benefits to thermal efficiency, are typically lower weight than their equivalent metallic components, and will continue to be applied to an increasing number of engine components (including more rotating parts) requiring strength and temperature capability. Finally, additive manufacturing opens up possibilities for better optimized design to bear loads, while reducing weight as compared to traditional components performing the same function.

The relative sizes of the propulsor and core are driven by the thrust requirements of a given aircraft and design decisions such as Time-on-Wing, bleed extraction and power extraction. The M&S optimization was expected to modify each of these parameters during the optimization process resulting a wide variety of potential engine configurations. The Propulsion Tahg therefore needed to provide weight information in a manner that captured changes in technology level that could be used to assess the various M&S configurations. As a notional example, an advanced fan case material might allow a 10% reduction in propulsor weight at a given fan diameter which represents a change in technology level. However, M&S optimization for a given application might select a 5% larger fan diameter as a lower fuel burn configuration which would result in a ~16% increase in propulsor weight at constant technology. When combined the propulsor weight in the aircraft level analysis would increase 5% (=(100-90)*116). The technology capability improvements were provided separately for the Propulsor and Core with each being independent of the other:

- Propulsor Weight reduction @ constant fan diameter (Propulsor = A-flange or aft fan case flange)
- Core Component Weight reduction @ constant core size (Core = LPC+HPC+Combustor+HPT+LPT)

Accounting for the overall effects of these different weight reduction technologies against engine sizing trends, relative to a 2018 TRA, 0-4% weight reduction in engine core components is possible by 2030, with 2-6% by 2040 and 4-8% by 2050, ranging from low to high progress scenarios. As an example of the Propulsion Tahg provided weight technology information, the core weight reduction trend (at constant core size) vs. EIS timing is listed in Table 4-3.

Table 4-3: Core Component Weight Reduction vs. EIS Date

		2018	2030	2040	2050
		2010 TRL6	2023 TRL6	2033 TRL6	2043 TRL6
WB	High Confidence	BASE	0%	2%	4%
	Med Confidence	BASE	2%	4%	6%
	Low Confidence	BASE	4%	6%	8%
NB	High Confidence	BASE	0%	2%	4%
	Med Confidence	BASE	2%	4%	6%
	Low Confidence	BASE	4%	6%	8%
RJ	High Confidence	BASE	0%	2%	4%
	Med Confidence	BASE	2%	4%	6%
	Low Confidence	BASE	4%	6%	8%
BJ	High Confidence	BASE	0%	2%	4%
	Med Confidence	BASE	2%	3%	5%
	Low Confidence	BASE	3%	4%	6%
TP	High Confidence	BASE	0%	2%	4%
	Med Confidence	BASE	2%	4%	6%
	Low Confidence	BASE	4%	6%	8%

4.5.6 Advanced Propulsion Concepts and Configurations (Complete Rewrite)

Through continuous improvement and substantial investment, the modern commercial engine has become one of the most efficient machines known to mankind while delivering remarkable levels of durability reliability and safety. However, it is becoming increasingly challenging to further optimize the Brayton cycle employed in traditional gas turbines powering commercial aircraft and therefore researchers are examining advanced and alternate concepts. The Propulsion Tahg worked collaboratively with the ACES Tahg in discussions on the fuel burn reduction impacts of these advanced propulsion systems on future ACA vehicles. A range of alternatives were identified and considered as part of the Tahg's data gathering process for concepts contained within the engine control volume, and those requiring larger architecture changes (see Figure 4-8).

4.5.6.1 Concepts and Configurations beyond the Engine Control Volume

The Propulsion Tahg's collaboration with the ACES Tahg identified a range of alternatives for propulsion concepts that would have large effects on and interdependencies with aircraft design, including changes in propulsor architecture (open rotor, boundary layer ingestion, and distributed propulsion concepts) as well as energy source (varying degrees of electrification, including hybridization, as well as non-drop in fuel sources, such as hydrogen). Consistent with the larger Technology SG's approach to ACA vehicle assessment, the Tahg agreed that rather than picking individual propulsion configurations as for specific vehicle classes in specific timeframes, a representative additional fuel burn delta from the ATW vehicle in a given aircraft class in a given year was determined, including impacts of airframe and propulsion technologies combined.

The Propulsion Tahg believes that a move to any of the advanced propulsion concepts considered would represent a one-time step-change in impacts on energy efficiency, from a propulsion perspective. These architecture changes would not modify the rate of improvement to the other fundamental parameters within the engine control volume, such as component efficiencies, materials properties advancement, etc. in any way that would be distinctly different from an ATW aircraft's evolutionary improvement over the years. This approach assumes that the initial version of an aircraft would take maximum advantage of the configuration with available technology. For example, while the configuration change of the aircraft fuselage on an ACA might open up constraints on engine fan diameter, once that design space is modified, further advancements are within the context of the components, materials, technologies within the propulsion system that are captured well by the ATW propulsion impacts. This conclusion supports the approach chosen to capture ACA vehicles impacts as a delta to the ATW vehicle in the same aircraft class in the same year. This approach relied upon review of research reports and past engineering experience of the Tahgs in order to quantify the potential benefits of new ACAs relative to ATW's in each vehicle size class.

Additional detailed discussion of the advanced propulsion configurations considered as part of the ACA assessment process are documented in Section 6.3.2.

4.5.6.2 Concepts within the Engine Control Volume

The Propulsion Tahg also reviewed advanced propulsion system concepts that were within the control volume of the propulsion system (see center element of Figure 4-8) in order to provide ACES with guidance on the readiness, attainability, and timing of these concepts. These are concepts which do not depend on new fuels and are approximately independent of the airframe configuration – i.e. they "fit within the covers" of traditional propulsion systems. Concepts that have a strong dependency on the airframe such as hydrogen, open rotors or distributed propulsion system were considered as potential integrated system ACAs in the ACES Tahg.

These advanced technology propulsion system concepts are primarily low TRL (typically TRL2) meaning that they are physically feasible and some fundamental building block components may have been proven at a design point condition in a laboratory environment. However, substantial research effort remains and there are practical challenges to be overcome before these propulsion systems become suitable for safe and reliable option in commercial revenue service. Based on stakeholder questionnaires and available open sources of data these technologies have not yet reached a maturity level suitable for transition from research facilities to industrial maturation. It is worth noting that most of these concepts have been known for many decades and may only now be enabled by new analytical capabilities, materials, and controls.

The Propulsion Tahg reviewed stakeholder questionnaires and available high-quality reports relevant to these concepts. The information was used as input to develop and provide the ACES Tahg with guidance on readiness, attainability and timing for consideration of potential improvements. The advanced concept cycles fall into the following broad categories that will be described further in this section:

- Pressure rise combustion
- Waste heat recovery or recuperation
- Intercooling
- Fluid augmentation

Pressure rise combustion

One area of potential large efficiency improvement is constant volume combustion, which may result in lower entropy generation and cooler exhaust streams than the conventional constant pressure Brayton processes. These concepts are relatively immature and require demonstration of the cycle across the full envelope and operating range, piston control and/or actuation, transient capability and reliable heat management systems in a medium TRL environment before being considered for industrial scale demonstration. There are several potential technologies in this area:

Piston based combustion through the composite cycles

Composite cycles combine conventional axial turbomachinery with piston engine components in order to achieve substantially higher OPR. Key challenges with this architecture are high operational temperatures of the piston system, very heavy core installation (up 40-50% increase in engine weight), reduced flow capacity at key pinch points in the mission, NO_x emissions, system volume, vibration and reliability. Some of these challenges could be mitigated by using intercooling at the expense of even further weight, volume and maintenance burden. Composite cycles have been studied for many decades, see Figure 4-17 [10], and many of the key mechanical challenges are yet to be mitigated. However, analytical studies continue on advanced designs suitable for commercial applications, as depicted in Figure 4-18 [11].

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10 Nomad 1, Napier & Son, 1949

11 Grönstedt, T., Xisto, C., Sethi, V. et al (2019) Conceptual design of ultra-efficient cores for mid-century aircraft turbine engines 24th ISABE conference

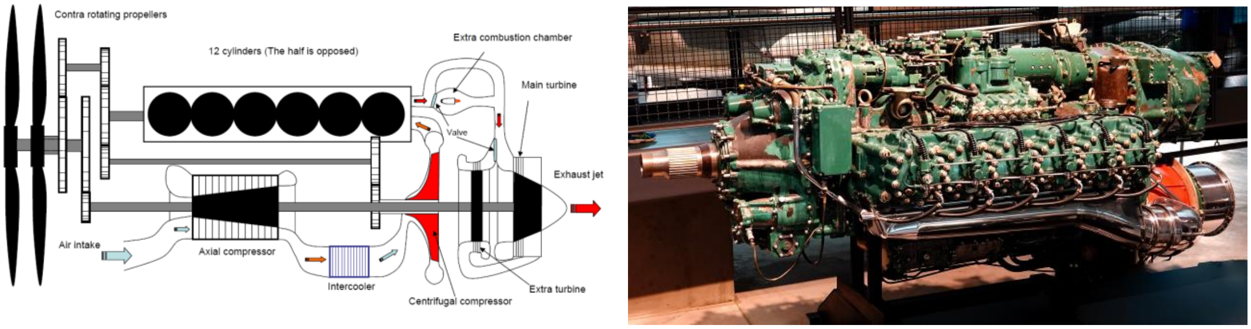

Figure 4-17. Composite cycle example

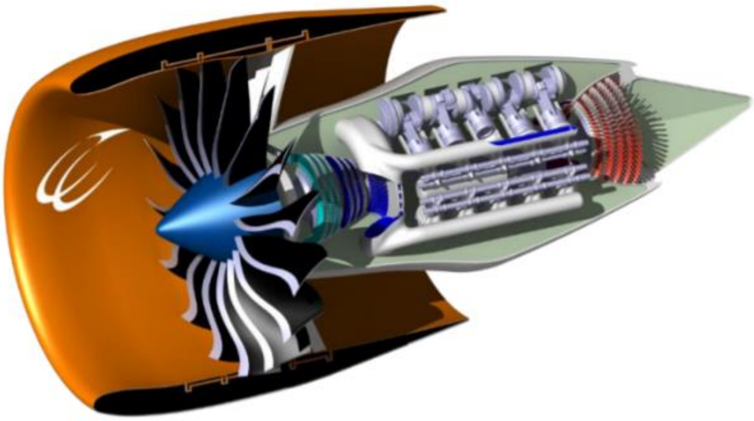

Figure 4-18. Advanced commercial engine study concept

Nutating disk

The nutating disc (ND) concept attempts to combine the cycle benefits of the piston engine without the weight, volume and vibration challenges and therefore might be more application for aircraft applications. The ND concept engine uses separate chambers for each element of the thermodynamic process. A unique feature of the ND engine is its ability to use both sides of its working disc during a full shaft revolution contributing to its potential for high power density. Figure 4-19 illustrates the components of a naturally-aspirated single disc ND engine [12]. The layout comprises an inlet, compression chamber, accumulator, combustion chamber, expansion chamber and exhaust manifold, with the nutating disc mounted inside the compressor and expander chambers. The excess power from the system is transmitted by a shaft which converts the nutating motion into a rotating motion. The main challenges of the ND concept are very uneven thermal loading during operation, seal deterioration, matching between the ND modules and adjacent turbomachinery, and scaling. Some of these challenges may be mitigated by two-disc arrangements that allow tuning of the system and improved thermal management. Due to mechanical limitations and very low TRL, studies have typically focused on application of ND to smaller, shorter life products such as Unmanned Aerial Vehicles.

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[12] Korakianitis, L. Meyer, M. Boruta, H.E. McCormick, Introduction and Performance Prediction of a Nutating-Disk Engine, J. Eng. Gas Turbines Power. 126 (2004) 294. doi:10.1115/1.1635394

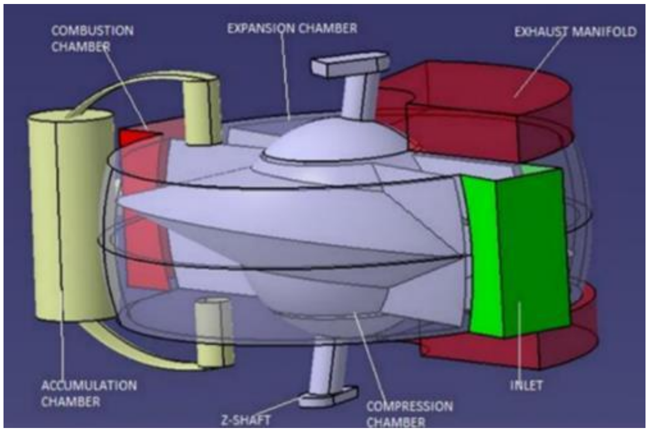

Figure 4-19. General arrangement of single-disc ND

Pulse detonation engines (PDE)

Conventional gas turbines are based on the deflagration of fuel via the rapid but subsonic combustion of fuel. PDEs operate on the principle of supersonic detonation of fuel which takes place so rapidly that the working fluid does not have time to expand and therefore takes place under quasi-constant volume. In principle PDE may offer the benefits of pressure rise combustion with lower mechanical complexity. However, there are substantial challenges that remain before PDE can be used in any application, and particularly for commercial aircraft. These challenges include packaging of components, reliable starting across the flight envelope, noise (often described as like a jackhammer), severe vibration, NO_x emissions and long-term durability due to high temperatures and cooling difficulties. PDE are considered very low TRL but are being actively researched for non-commercial applications that may mitigate some of the fundamental difficulties. Additional research will be required for commercial requirements such as noise and emissions.

Bottoming cycles and recuperation

Bottoming cycles and recuperation recover heat from the primary engine exhaust with an additional closed cycle, often implemented using a closed Brayton cycle using supercritical carbon dioxide as its working fluid. The recovered heat energy from the core exhaust flow is used to generate additional power for the low-pressure shaft of the turbofan. The concept is summarized in Figure 4-20 [13]. It is important to note that the components are not to scale and the supercritical carbon dioxide turbomachinery components would be even smaller relative to the main engine components due to the substantially higher-pressure levels. The colors are indicative of the gas-path temperatures in each component, with blue being cold and red being hot. Bottoming cycles are used in ground-based power generation application and the concept is generally understood. However, transitioning the concept to flight applications will require developments in high thermal gradient heat exchangers, failure tolerant systems integration, and sub-system packaging.

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[13] F. Jacob, R. A., S. J., V. Sethi, M. Belmonte and P. Cobas, "Performance of a Supercritical CO_2 Bottoming Cycle for Aero Applications," Appl. Sci., vol. 7, no. 3, 2017

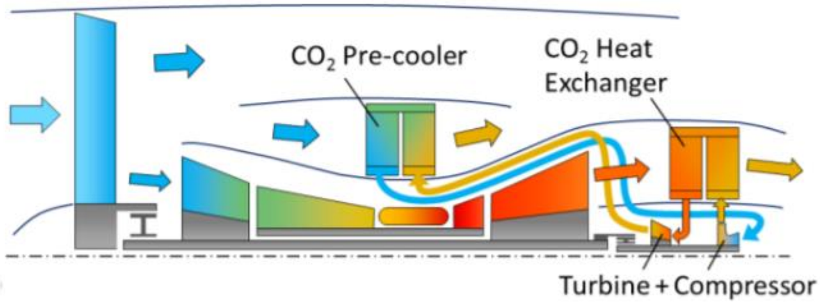

Figure 4-20. Notional Architecture for a Bottoming Cycle with Recuperation

Intercooling

Intercooling employs heat exchange in the compression system to reduce the temperature of the core flow. This enables increased overall pressure ratio and/or decreased compressor discharge temperature. Intercooling helps increase core specific power and can be used to reduce NOx emissions. Intercooling is well suited to being combined with other advanced concepts such as pressure rise combustion because it reduces temperatures reducing the mechanical and emissions challenges inherent with those concepts. The primary challenge of intercooling is the mechanical integration and weight of high efficiency heat exchangers which tend to be very large within the fan stream and core stream. Currently, the negative impacts of mechanical integration have not been sufficiently mitigated to enable application to a commercial engine.

Fluid enhanced cycles

Water was used in the past to improve thrust and emissions for a short duration during the take-off phase of the flight. Modern engines are now challenged for temperature capability and durability, and emissions, at top of climb and in cruise. Therefore, research is on-going on how to use water in steady state to yield efficiency improvements and NO_x reduction, a notional depiction is provided in Figure 4-21 [14]. Carrying sufficient water for this purpose would be prohibitively heavy and therefore concepts such as using exhaust from fuel cell Auxiliary Power Units or recovering water from the main engine exhaust are being assessed. An example of these cycles is the Water Enhanced Turbofan which condenses water from the engine exhaust and then uses to the core exhaust to generate steam which is then injected into the core. This cycle may offer improved efficiency, reduced NO_x and reduced contrails. The configuration is currently low TRL with on-going fundamental research and development in the area of condensers, heat exchangers, high humidity combustion and climate impact. Challenges include off-design and transient operation, controls, component volume and real-world effects such as icing, dirt and failure conditions.

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14 Pouzolz, R.; Schmitz, O.; Klingels, H. Evaluation of the Climate Impact Reduction Potential of the Water-Enhanced Turbofan (WET) Concept. Aerospace 2021, 8, 59. https://doi.org/10.3390/aerospace8030059

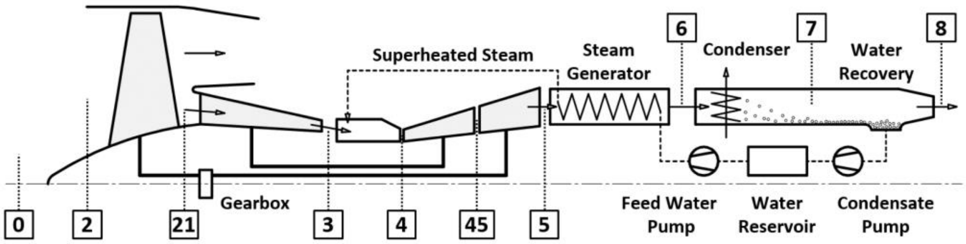

Figure 4-21. Water Enhanced Turbofan

4.5.7 Interdependencies

During the process of reviewing existing, foreseen and innovative propulsion technologies for consideration of their impacts on fuel burn of future aircraft, the Propulsion Tahg also considered the effect that new technologies may have on other key environmental metrics (including noise and non-CO_2 engine emissions). While no quantitative analysis of impacts on these metrics was run as part of the LTAG effort, a qualitative discussion was conducted.

In general, the Tahg concluded that technologies improving efficiency of propulsion systems on ATW aircraft will yield at a minimum noise-neutral results relative to current technologies, if not yielding noise reductions. However, in the case of propulsion technologies that alter the energy source of the propulsion system, weight can often be impacted. For example, introduction of hybrid power components to the engine, or a change to hydrogen as a fuel, will result in a heavier overall aircraft for a given number of passengers or payload, and as a result the aircraft may be louder during takeoff and landing operations.

For full ACA aircraft architectures, the impacts on interdependencies are highly configuration-dependent. Some of these may offer challenges to noise (e.g. BLI and open rotor propulsion configurations will likely increase source noise vs. a conventional ducted turbofan of similar thrust), while other configurations may yield noise reductions (e.g. shielding of engine noise radiating downward to the ground, or lower takeoff thrust requirements). This is further discussed in Section 6.3.2. However, no specific advanced propulsion configuration was selected for the ACA assessment activity. Rather, the energy efficiency benefits of a range of configurations were captured as part of the advanced concept aircraft improvements over the advanced tube and wing aircraft.

With respect to non-CO_2 emissions, for a jet fuel-powered engine, combustor technology is a primary driver of NO_x and non-volatile particulate matter (nvPM). As engine OPR increases with technology development focused on thermal efficiency, combustor inlet temperature (T3) rises, making the challenge to further reducing NO_x more difficult. Concerted research and development effort will be needed to maintaining or further reducing NO_x emissions as OPR and T3 rises. As described in the IEIR report, advanced combustion technologies currently applied to larger engine sizes require development to be able to yield similar emissions reductions benefits on smaller engine sizes. nvPM emissions will be highly dependent upon lean vs. rich-burn combustion architectures in future designs, but, for the purpose of the LTAG exercise, are largely independent of technologies increasing fuel efficiency and decreasing CO_2 emissions from future engines.

4.6 Impact of Cruise Speed on Fuel Reductions

Aircraft cruise speed reduction has been acknowledged in the literature as one way to reduce aircraft fuel consumption. Since drag is proportional to square of the flight speed, flying slower will provide some fuel savings if aircraft are designed for these speeds [15]. Economon analyzed the impact of cruise speed reduction and found that moving from Mach 0.84 to 0.70 will allow for a 13.1% fuel savings but 11.4% of these savings have been realized at Mach 0.74 [16]. The Subsonic Ultra Green Aircraft Research (SUGAR) study acknowledged that if meeting the NASA fuel burn goal was the only objective, aircraft cruise speed would be Mach 0.60. However, economic concerns set the minimum cruise Mach to 0.70. It should be noted that lower speeds increase the operating costs on airlines as well as reduce the utilization of the aircraft.

Two key changes enable the improved fuel burn at lower cruise speeds, namely wing and engine redesign: wing redesign occurs because the sweep is reduced while the thickness is increased. Less sweep creates a lighter wing and this translates into fuel savings. Engine redesign improves the cruise performance as the lower cruise speed results in less energy in the airflow entering the engine. Given the existing temperature limits of materials, this means that the engine can operate under higher pressure ratios and allows for more efficient combustion. These work together to provide fuel savings [15]. This reference provides plots of percent fuel burn reduction with cruise Mach number variation for different vehicles ranging from regional jets to large twin aisle. Data points visually extracted from this reference indicate mission fuel burn savings ranging from -2.6% to -8.8% over the respective baseline vehicles of each class as depicted in Figure 4-22. Greater fuel burn savings trend with larger vehicle classes and the savings tend to be maximized around M = 0.7, with a resized vehicle.

The NASA SUGAR project [17] and media reports have acknowledged that “some airlines have recently reduced cruise speeds to increase efficiency” [18]. In the SUGAR report, an initial sizing process is used (discussed in Section 5.1.3) where several vehicles are optimized for varying cruise Mach numbers. The initial cruise altitude (ICA) was allowed to vary but was limited to 43,000 ft. The fuel burn for these optimized aircraft is shown in Figure 4-22 as replicated from [15]. Each vehicle is optimized to minimize fuel burn for the given Mach number and their results plot clearly shows an advantage for slowing down. It should be noted that SUGAR adheres to the lower limit of Mach 0.70 for medium sized airplanes as suggested by the Boeing Current Market Outlook (CMO), “although Mach 0.7 minimizes fuel burn, higher cruise speed should be considered for its increase in productivity and thus higher economic value.”.

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15 Brett, P., A Methodology for Evaluating Fleet Implications of Mission Specification Changes, Georgia Institute of Technology Dissertation, December 2014

16 Economon, T; Copeland, S; Alonso J. Design and optimization of future aircraft for assessing the fuel burn trends of commercial aviation. In *49th AIAA Aerospace Sciences Meeting*, 2011.

17 Bradley, M. and Droney, C., Subsonic Ultra Green Aircraft Research: Phase I Final Report, NASA/CR–2011-216847

18 MSNBC (May 1, 2008); Airlines slow down flights to save on fuel, Retrieved May 20, 2008 from http://www.msnbc.msn.com/id/24410809/

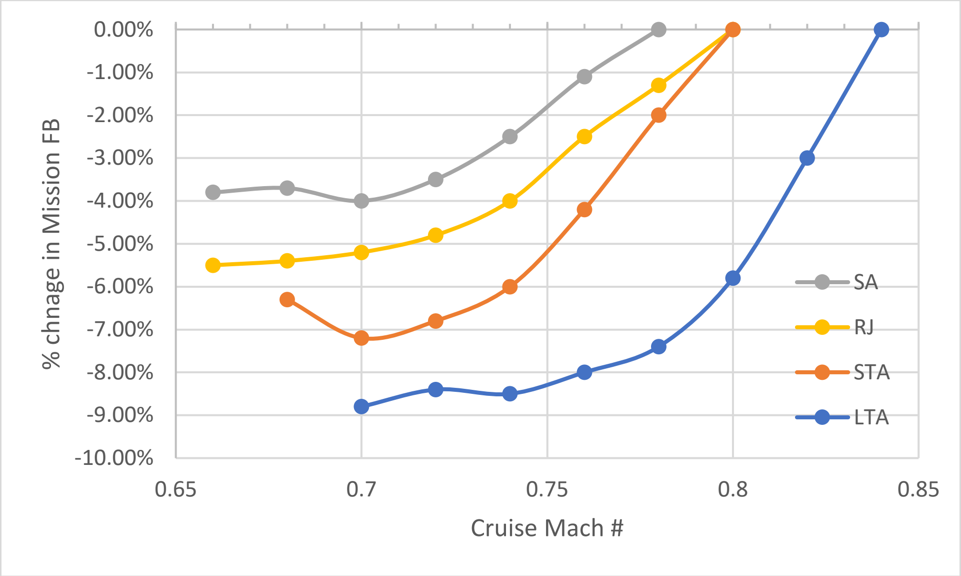

Figure 4-22. Percent Change in Fuel Burn with Cruise Mach # Variation for four vehicle classes

The SUGAR study phase I final report indicates that a fuel burn trade was performed with Mach number in their Refined SUGAR concept (2030 Reference Configuration); noting that these designs were a clean sheet aircraft and not just taking the existing aircraft and flying slower speeds. In this study, the span constraint was active leaving wing area, thickness to chord ratio, and sweep as the highest-level optimization variables of interest. The results show the fuel optimum at M = 0.70 with a fuel burn of 6,388 lbs for a 900 nmi mission compared to their SUGAR Free (2008 Baseline Configuration) which had FB of 12,681 lbs on the 900 nmi mission. However, the phase II final report notes that, "although Mach 0.70 minimizes fuel burn, higher cruise speed should be considered for its increase in productivity and thus higher economic value" [19].

This review found that significant fuel burn savings are well-documented in the literature at lower cruise speeds due to the lower drag conditions, particularly if the wing and engine are resized, which implies a clean sheet designed aircraft and engine. However, the minimum commercially acceptable cruise speed seems to be M 0.70, below which economic utilization concerns may offset fuel savings for operators.

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19 Bradley, M. and Droney, C., Subsonic Ultra Green Aircraft Research: Phase II – Volume I – Truss Braced Wing Design Exploration, NASA/CR–2015-218704

APPENDIX M3.5. ADVANCED TUBE AND WING MODELING APPROACH AND RESULTS

5.1 INTRODUCTION

ATW assessment process is comprised of seven steps as depicted in Figure 5-1. below. These phases include notional aircraft selection for each class (i.e. TRAs), model calibration in the M&S tool, technology impact identification for 2030/2040/2050 as defined by the Airframe and Prop Tahgs, technology impact implementation into M&S tool, vehicle level benefit quantification, technology and vehicle scenario-based projection, cost estimation and investment quantification. Each phase is elaborated upon in the following subsections with each step described in detail.

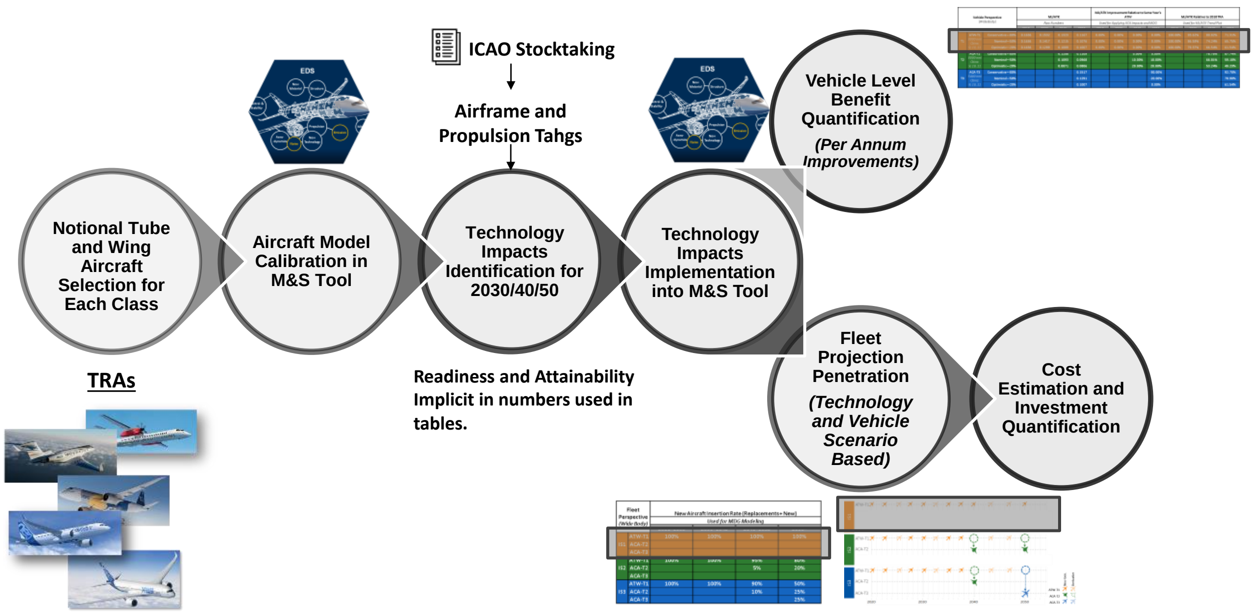


Figure 5-1. ATW Assessment Process

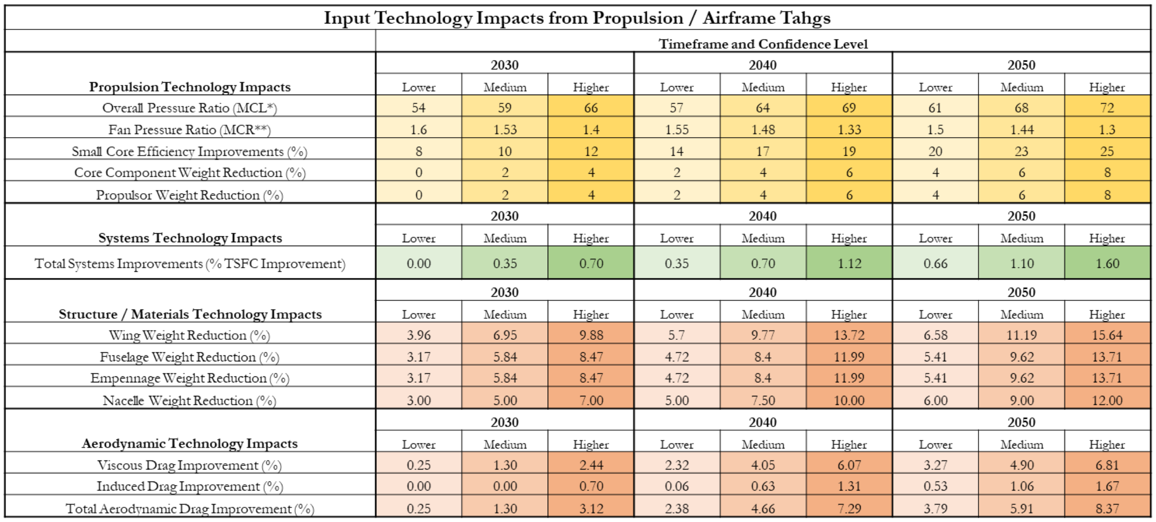
5.2 ATW MODELING AND SIMULATION METHODOLOGY

In the first phase of the ATW assessment process, a notional technology reference aircraft (TRA) from the current fleet is chosen for each passenger class. These passenger classes are binned into categories of similar sized vehicles and five notional vehicles are chosen to represent all the classes. The first bin is the turboprop size which includes greater than 19 passengers and up to 85 passengers and is best represented by a notional DHC Dash 8-400 aircraft. The second bin comprises regional jets from 20 to 100 passengers and is represented by a notional E190-E2 aircraft. The third bin is made up of narrow body jets from 101 to 210 passengers represented by a notional A320neo aircraft. The fourth bin is composed of wide body jets from 211 to more than 400 passengers as well as freighters, and is represented by a notional A350-900 aircraft. The final bin comprises business jets and is represented by a notional Gulfstream G650 aircraft. These notional TRAs are used as baselines for comparison to assess aircraft performance in the 2030, 2040, and 2050-time frames.

In the second phase of the ATW assessment process, the aircraft model calibration is performed in the selected modeling and simulation tool. This study chose to use the EDS tool for aircraft level assessment due to its accuracy, fidelity, and flexibility. A detailed description of how EDS works and its structure is provided in Annex B.

EDS models the TRA, which are based on a technology level in line with state-of-the-art of the vehicles currently in production. For example, in the wide body sample problem, the TRA is based on the A350-900 and has an 8,000 nm design range. The top-level metrics identified for the TRA are related to fuel burn including the total trip fuel and the fuel burn per available-ton-kilometer (R_1 range). Once the TRA models are calibrated to their in-service equivalent aircraft and assessed, the future technology impacts are applied to these baseline vehicles. It should be noted that unlike the IEIR study which considered noise and emissions, the LTAG modeling only considered fuel burn as the proxy for the long-term aspirational goal of reducing CO_2.

In the third phase of the ATW assessment process, the technology impacts are identified in four categories from their respective Tahgs: propulsion technology impacts, system technology impacts, structures/materials technology impacts, and aerodynamic technology impacts. In each category, technology impacts are identified for the 2030, 2040, and 2050 timeframes. In each of the three timeframes lower, medium, and higher progress confidence levels are identified for achieving introduction of the technology baskets on future integrated aircraft designs. An example of wide body impacts is provided in Figure 5-2 below.



Input Technology Impacts from Propulsion / Airframe Tahgs									
	Timeframe and Confidence Level								
	2030			2040			2050		
Propulsion Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Overall Pressure Ratio (MCL*)	54	59	66	57	64	69	61	68	72
Fan Pressure Ratio (MCR**)	1.6	1.53	1.4	1.55	1.48	1.33	1.5	1.44	1.3
Small Core Efficiency Improvements (%)	8	10	12	14	17	19	20	23	25
Core Component Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Propulsor Weight Reduction (%)	0	2	4	2	4	6	4	6	8
	2030			2040			2050		
Systems Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Total Systems Improvements (% TSFC Improvement)	0.00	0.35	0.70	0.35	0.70	1.12	0.66	1.10	1.60
	2030			2040			2050		
Structure / Materials Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Wing Weight Reduction (%)	3.96	6.95	9.88	5.7	9.77	13.72	6.58	11.19	15.64
Fuselage Weight Reduction (%)	3.17	5.84	8.47	4.72	8.4	11.99	5.41	9.62	13.71
Empennage Weight Reduction (%)	3.17	5.84	8.47	4.72	8.4	11.99	5.41	9.62	13.71
Nacelle Weight Reduction (%)	3.00	5.00	7.00	5.00	7.50	10.00	6.00	9.00	12.00
	2030			2040			2050		
Aerodynamic Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Viscous Drag Improvement (%)	0.25	1.30	2.44	2.32	4.05	6.07	3.27	4.90	6.81
Induced Drag Improvement (%)	0.00	0.00	0.70	0.06	0.63	1.31	0.53	1.06	1.67
Total Aerodynamic Drag Improvement (%)	0.25	1.30	3.12	2.38	4.66	7.29	3.79	5.91	8.37

Figure 5-2. Example of Wide Body Technology Impacts

In the fourth phase of the ATW assessment process, the technology impacts are implemented into the M&S tool, which is EDS, as shown in Figure 5-3. This is a structured process with multiple steps in order to ensure accuracy. After the calibration of TRA and implementation of technology impacts for each time frame to TRA, the next step is to determine which design parameters to vary or not, and to identify the constraints. It should be noted that the TRA results were deemed fit for purpose by the Tech SG as the point of departure for the technology impacts. Subsequently, each of the actual in-service aircraft on which the TRAs are based were optimized to a particular set of objectives defined by the manufacturers to produce a competitive product for the market, but the exact parameters optimized are not the same as those in the EDS modeling and the industry objectives are unknown to the Tech SG and also the modeling team. Therefore, each of the TRAs were optimized at the 2018 TRA technology levels within the ranges of the design parameters feasible in 2017, which were defined by the Tahgs, subject to a set of constraints. This would serve as the basis for the ATW improvements in FB/ATK and energy intensity.

The design parameters that were fixed for technology infused vehicles include design range, design payload, design cruise Mach number, field length requirements, sweep angle, average thickness-to-chord ratio. The design variables that are varied to perform design space exploration and optimization for a given technology level are: wing loading, thrust to weight ratio, aspect ratio, combustor exit temperature and the fan pressure ratio. Ranges were determined for these EDS design variables and applicable constraints for each timeframe, as provided by the Airframe and Propulsion Tahgs.

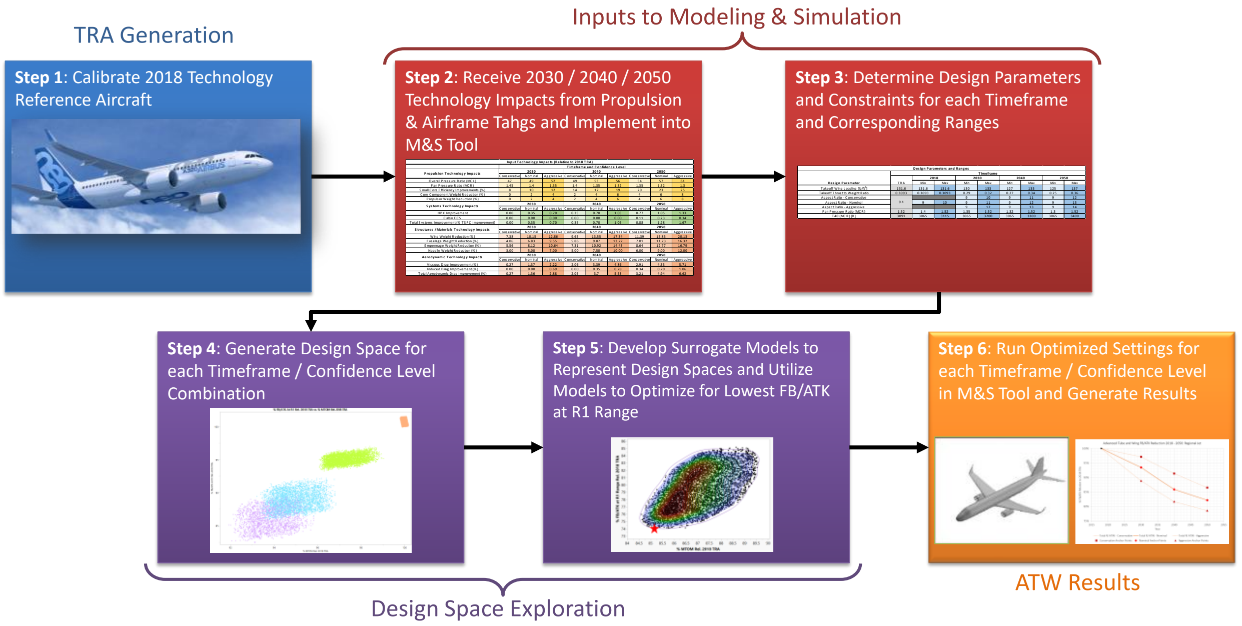


Figure 5-3. ATW Modeling Methodology

To enable rapid exploration of the design space, a Design of Experiments (DoE) was defined to create surrogate models of fuel burn at R_1 and the design range as a function of the design parameters and technology impact factors. Once created, a time frame and a technology progress level were fixed and uniform distributions of the design variables were assessed to create a “cloud” of possible optimal ATWs to select, as shown as Step 4 in Figure 5-3. Based on the “clouds”, all configurations that did not meet the constraints were filtered out and then a subset of lowest FB/ATK at R_1 were selected and inspected for trends over time across the design parameters. For example, does the progression in aspect ratio for a NB seem reasonable for a given technology progress level based on review of the Tahgs? The TRA are also optimized for fuel burn to ensure that the comparison between TRA and ATW is a reasonable one. The final designs for each time frame are selected as the designs that have the minimum fuel burn at R_1 compared to optimized 2018 TRA.

Once the ATW for a given time frame was selected, the FB/ATK improvement was calculated relative to the optimized TRA. To obtain the per annum improvements relative to the TRA to provide to MDG, the optimal ATW needs to be shifted relative to the difference in the TRA and the optimal TRA to ensure an apple to apples comparison to provide to MDG. This is calculation is notionally depicted in Figure 5-4.

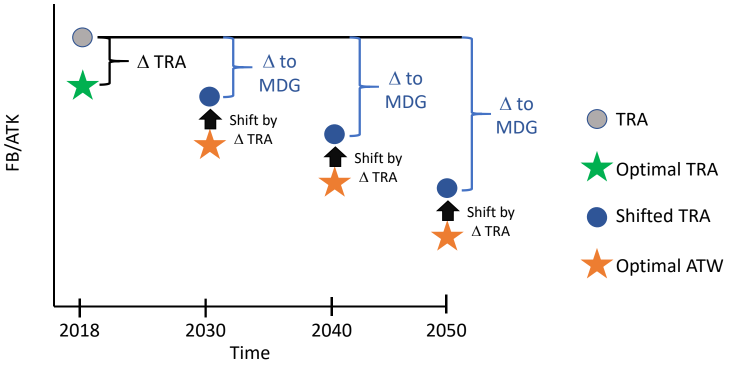


Figure 5-4. Notional ATW Fuel Burn per ATK Calculations

In the fifth phase of the ATW assessment process, the vehicle level benefits are quantified from the M&S tool in the previous phase. The optimized vehicle results are determined at the R_1 range but the final results to be passed on to MDG are quantified at the design range. The results include Maximum Take-off Mass (MTOM) and FB/ATK projections in the 2030/2040/2050 timeframes at the lower, medium, and higher technology progress levels. FB/ATK values are automatically calculated by EDS using Equation 5-1 below, where the weights are in kg-tonnes, and the range is in kilometers.

$$FB/ATK = \frac{Trip\ Fuel}{ATK} = \frac{Block\ Fuel - Taxi\ Out\ Fuel}{(Zero\ Fuel\ Weight - Empty\ Weight) \times Range} \qquad \text{5-1}$$

A sample of the projected results with % decrease in FB/ATK and the band formed at the various confidence levels is shown in Figure 5-5.

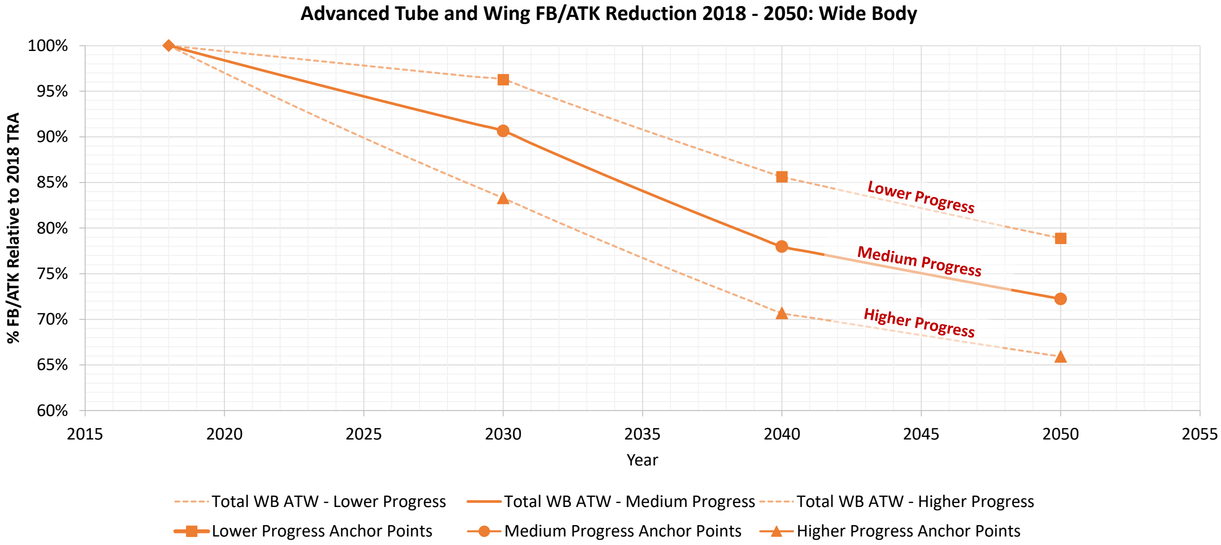


Figure 5-5. ATW Fuel Burn per ATK Benefits with Time

In the sixth phase of the ATW assessment process, the vehicle level results are projected for future technology and vehicle scenarios to assess fleet penetration in 2030/2040/2050. There are three technology scenarios and each contains low, medium, and high progress level projections. They all incorporate per annum energy intensity changes relative to previous decade, ATW/TRA in units of %Megajoules/ATK. The fleet penetration will be governed by a market split between ATW and ACA vehicles as well as future demand scenarios and production rate considerations, which will be discussed in APPENDIX M3.7. The final phase of the ATW assessment process is to approximate cost estimation and investment requirements for technology maturation and introduction. In this phase, various cost elements are considered including R&D costs, manufacturer's non-recurring costs, and a scoped degree of operations and fuel costs. The scope is determined through coordination with the other Tahgs and MDG/FESG, and may include qualitative cost analysis for some elements. The costs associated with the ATWs were determined in coordination with the Cost Estimation ad hoc group. After the ATW aircraft are quantified, the ACAs are then assessed using the methodology in the next Chapter.

5.3 ATW RESULTS

The ATW assessment process was applied to each vehicle class for each time frame under consideration. For the technology impacts, the Airframe Tahg provided total system improvements that would result in SFC reduction, and airframe component weight reductions and aerodynamic improvements in viscous and induced drag, which were modeled in EDS as the total change in drag. The Propulsion Tahg provided target efficiencies for the engine turbomachinery components at the maximum cruise (MCR) condition, which was equivalent to the aero design point (ADP) in EDS. These component efficiencies consisted of the adiabatic efficiencies for the fan and the turbines, and the polytropic efficiencies for the multi-stage compressors (LPC and HPC). These target efficiencies were provided for each timeframe and confidence interval, and illustrated trends in engine component technology development that were consistent with the estimations from the different Propulsion Tahg members.

In addition, the Propulsion Tahg delivered impacts for OPR at the maximum climb (MCB) condition, which was equivalent to the cruise top of climb (TOC) condition in EDS. FPR targets were also specified at the ADP condition. However, it is important to note that the FPR provided by Propulsion Tahgs represents a notional FPR value to calibrate the target engine component efficiencies. FPR was allowed to vary during the ATW optimization process. The small core efficiency improvements were implemented at a constant engine core size and translated to a polytropic efficiency loss. Additional weight reductions were also provided for the core components and the propulsion system, as a whole. The technology impacts were provided by the Tahgs and are listed in Annex D for each vehicle class, time frame, and progress level.

The design variables utilized for the optimization of the TRASs included takeoff wing loading, takeoff thrust to weight ratio, aspect ratio, fan pressure ratio, and the combustor exit total temperature (T40). Each vehicle was constrained to a compressor exit temperature (T3max), a fan diameter, and a gate constraint (effectively wing span). The fan diameter constraint was set to ensure at least two feet of ground clearance for the engine for all vehicle classes. For the RJ, NB, and WB, if the wing span exceeds the threshold of the gate constraint, a folding wing tip device was added to meet the constraint. The NB wing weight penalty was 4.4% and 6.6% for the WB, which resulted in a 10% drag penalty for the WB. The design variable values and constraints utilized for the optimization of each class are provided in Annex E.

With the technology impact and design variable ranges defined, a DoE was executed to create surrogate models of fuel burn per ATK at the R_1 and design range. For a given time frame and progress level, the design variables were varied with a uniform distribution to obtain the optimal ATW "clouds", which were filtered to contain only those designs that met the constraints. The WB medium progress clouds of %FB/ATK at R_1 versus MTOM relative to the 2018 TRA are depicted in Figure 5-6. The "clouds" were explored for the region of optimal designs (lower left for each cloud with maximum fuel burn reduction at R_1 and minimum MTOM) for repeated patterns, design variable trends, and performance with progress level and time frame. Once selected, the fuel burn at the design range was determined.

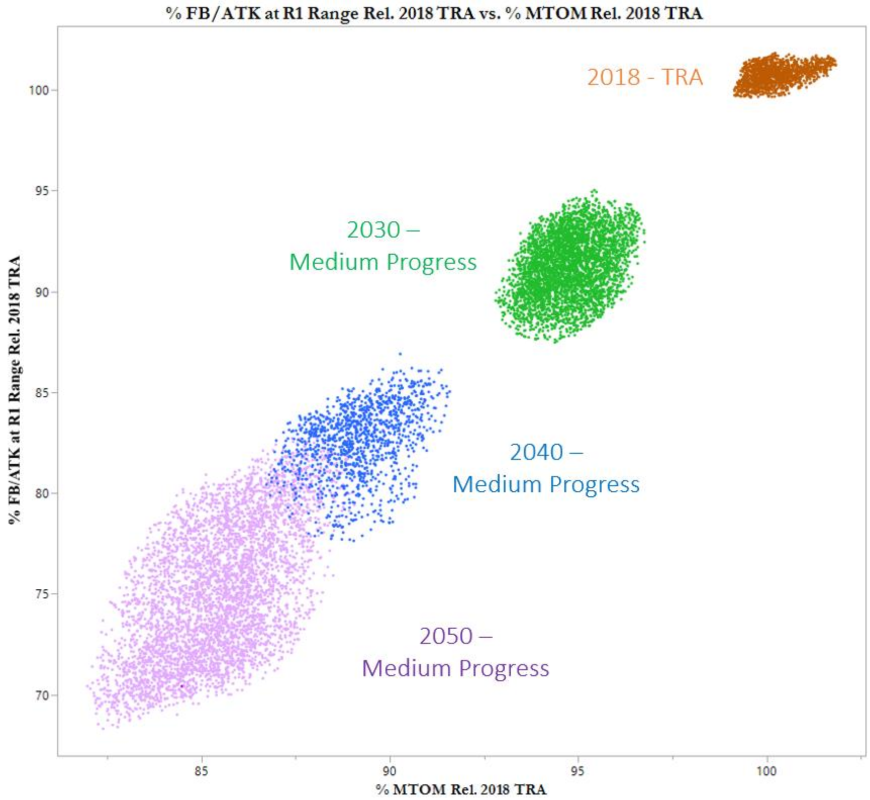


Figure 5-6. WB ATW Optimization Clouds for Medium Progress

Once the optimal design for each time frame, progress level, and vehicle were determined, the FB/ATK improvements at the design range relative to the 2018 optimized TRA were calculated. Based on the notional logic of shifting the optimal ATW to reference to the 2018 TRA, the FB/ATK and MTOM were shifted based on the difference between the 2018 non-optimized TRA and the 2018 optimal TRA. The shift values utilized for each vehicle are listed in Table 5-1 and the resulting FB/ATK per annum relative to the 2018 TRA and also relative to the previous decade, which is the value utilized by MDG, were determined. It is important to note that for the TP and RJ airframes, the TRA was found to be at an already optimum level given the bounds of the design variables explored. Therefore, no shift was required. The results for the TP, BJ, RJ, NB, and WB are listed in Table 5-2 through Table 5-6 and plotted in Figure 5-7 through Figure 5-11, respectively.

Table 5-1: Shift Values from 2018 Optimized TRA to the Non-optimized TRA s

Aircraft	FB/ATK at Design Range
TP	0.0000
BJ	0.0193
RJ	0.0000
NB	0.0037
WB	0.0031

Table 5-2 through Table 5-6 lists a high-level summary of the ATW results for each aircraft class. This summary consists of MTOM, FB/ATK at their design range, percentage FB/ATK with respect to the 2018

TRA, and per annum improvements. These results have been grouped for each timeframe (2030, 2040, and 2050) and confidence interval (lower, medium, and higher progress).

Table 5-2: TP ATW Results at the Design Range

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK Per Annum (Rel. 2018 TRA)	FB/ATK Per Annum (Rel. Previous Decade)
2018	**TRA**	29,577	0.2058			
2030	**Lower Progress**	28,692	0.1929	-6.23%	-0.53%	-0.53%
	Medium Progress	28,077	0.1812	-11.96%	-1.06%	-1.06%
	Higher Progress	27,522	0.1730	-15.93%	-1.44%	-1.44%
2040	**Lower Progress**	28,050	0.1814	-11.86%	-0.57%	-0.62%
	Medium Progress	27,221	0.1691	-17.83%	-0.89%	-0.69%
	Higher Progress	26,595	0.1604	-22.05%	-1.13%	-0.75%
2050	**Lower Progress**	27,659	0.1758	-14.57%	-0.49%	-0.31%
	Medium Progress	26,876	0.1630	-20.76%	-0.72%	-0.36%
	Higher Progress	26,177	0.1541	-25.13%	-0.90%	-0.40%

Table 5-3: BJ ATW Results at the Design Range

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK Per Annum (Rel. 2018 TRA)	FB/ATK Per Annum (Rel. Previous Decade)
2018	**TRA**	46,992	0.6341			
2030	**Lower Progress**	43,802	0.6041	-4.74%	-0.40%	-0.40%
	Medium Progress	42,409	0.5740	-9.48%	-0.83%	-0.83%
	Higher Progress	41,861	0.5539	-12.66%	-1.12%	-1.12%
2040	**Lower Progress**	42,683	0.5709	-9.98%	-0.48%	-0.56%
	Medium Progress	40,964	0.5377	-15.21%	-0.75%	-0.65%
	Higher Progress	39,343	0.5067	-20.10%	-1.01%	-0.89%
2050	**Lower Progress**	41,302	0.5402	-14.82%	-0.50%	-0.55%
	Medium Progress	39,761	0.5078	-19.92%	-0.69%	-0.57%
	Higher Progress	38,037	0.4753	-25.04%	-0.90%	-0.64%

Table 5-4: RJ ATW Results at the Design Range

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK Per Annum (Rel. 2018 TRA)	FB/ATK Per Annum (Rel. Previous Decade)
2018	**TRA**	56,400	0.1726			
2030	**Lower Progress**	55,390	0.1677	-2.87%	-0.24%	-0.24%
	Medium Progress	54,539	0.1613	-6.55%	-0.56%	-0.56%
	Higher Progress	53,356	0.1534	-11.14%	-0.98%	-0.98%
2040	**Lower Progress**	54,371	0.1577	-8.65%	-0.41%	-0.61%
	Medium Progress	53,053	0.1483	-14.12%	-0.69%	-0.84%
	Higher Progress	52,012	0.1410	-18.35%	-0.92%	-0.84%
2050	**Lower Progress**	53,713	0.1494	-13.49%	-0.45%	-0.54%
	Medium Progress	52,505	0.1418	-17.85%	-0.61%	-0.44%
	Higher Progress	51,549	0.1356	-21.44%	-0.75%	-0.38%

Table 5-5: NB ATW Results at the Design Range

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK Per Annum (Rel. 2018 TRA)	FB/ATK Per Annum (Rel. Previous Decade)
2018	**TRA**	79,000	0.1575			
2030	**Lower Progress**	76,252	0.1512	-3.99%	-0.34%	-0.34%
	Medium Progress	74,411	0.1405	-10.78%	-0.95%	-0.95%
	Higher Progress	72,684	0.1303	-17.26%	-1.57%	-1.57%
2040	**Lower Progress**	74,105	0.1369	-13.10%	-0.64%	-0.99%
	Medium Progress	72,492	0.1278	-18.87%	-0.95%	-0.95%
	Higher Progress	70,833	0.1194	-24.21%	-1.25%	-0.87%
2050	**Lower Progress**	73,210	0.1281	-18.68%	-0.64%	-0.66%
	Medium Progress	71,135	0.1194	-24.20%	-0.86%	-0.68%
	Higher Progress	69,623	0.1134	-27.97%	-1.02%	-0.51%

Table 5-6: WB ATW Results at the Design Range

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK Per Annum (Rel. 2018 TRA)	FB/ATK Per Annum (Rel. Previous Decade)
2018	**TRA**	280,000	0.1979			
2030	**Lower Progress**	276,585	0.1905	-3.73%	-0.32%	-0.32%
	Medium Progress	267,442	0.1794	-9.35%	-0.81%	-0.81%
	Higher Progress	253,440	0.1648	-16.70%	-1.51%	-1.51%
2040	**Lower Progress**	268,138	0.1694	-14.38%	-0.70%	-1.17%
	Medium Progress	255,106	0.1543	-22.02%	-1.12%	-1.49%
	Higher Progress	240,933	0.1399	-29.30%	-1.56%	-1.63%
2050	**Lower Progress**	260,628	0.1561	-21.11%	-0.74%	-0.82%
	Medium Progress	247,160	0.1429	-27.76%	-1.01%	-0.76%
	Higher Progress	233,211	0.1304	-34.07%	-1.29%	-0.70%

This data has been plotted in Figure 5-7 to Figure 5-11 to better illustrate the FB/ATK improvements across decades. This shows the projected improvements in aircraft fuel burn efficiency given the technology impacts provided by the Tahgs and after following the optimization process described previously. It is observed how all airframes follow similar improvement trends. However, the potential percentage improvements are lower for the smaller aircraft classes (TP, BJ, and RJ) than the larger classes (NB and WB). This is explained by the fact that the smaller aircraft had TRAs that were produced earlier (such as the RJ), the decrease in the potential benefits achievable via technology infusions, and the shorter ranges that prevent the airframes from realizing greater fuel burn reductions over the course of their mission.

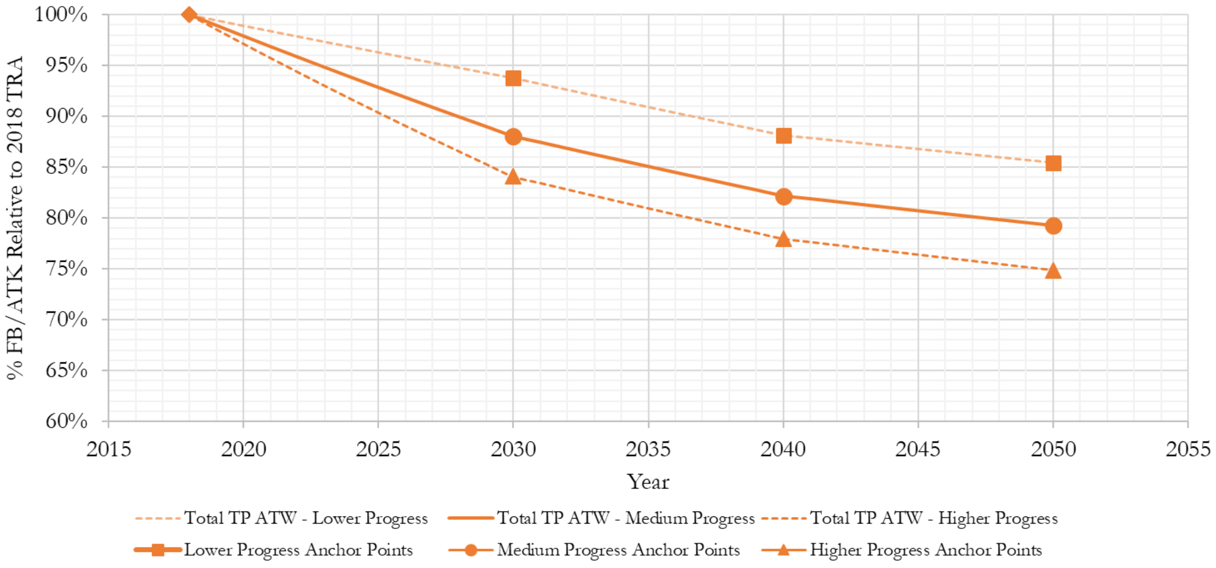


Figure 5-7. TP ATW FF/ATK Improvements Relative to the previous Decade

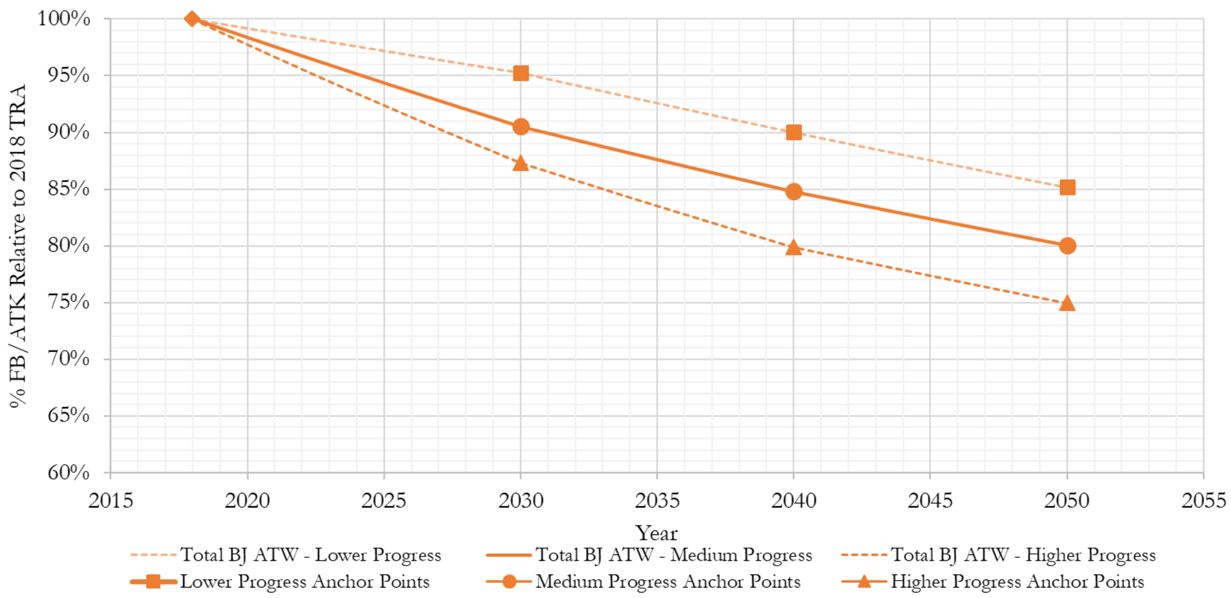


Figure 5-8. BJ ATW FF/ATK Improvements Relative to the previous Decade

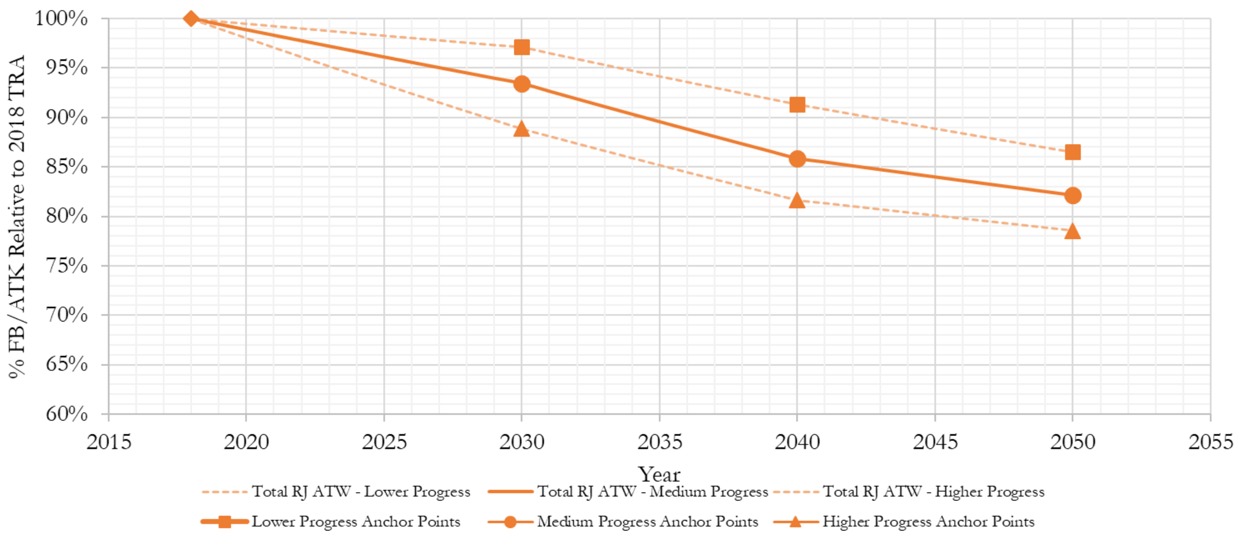


Figure 5-9. RJ ATW FF/ATK Improvements Relative to the previous Decade

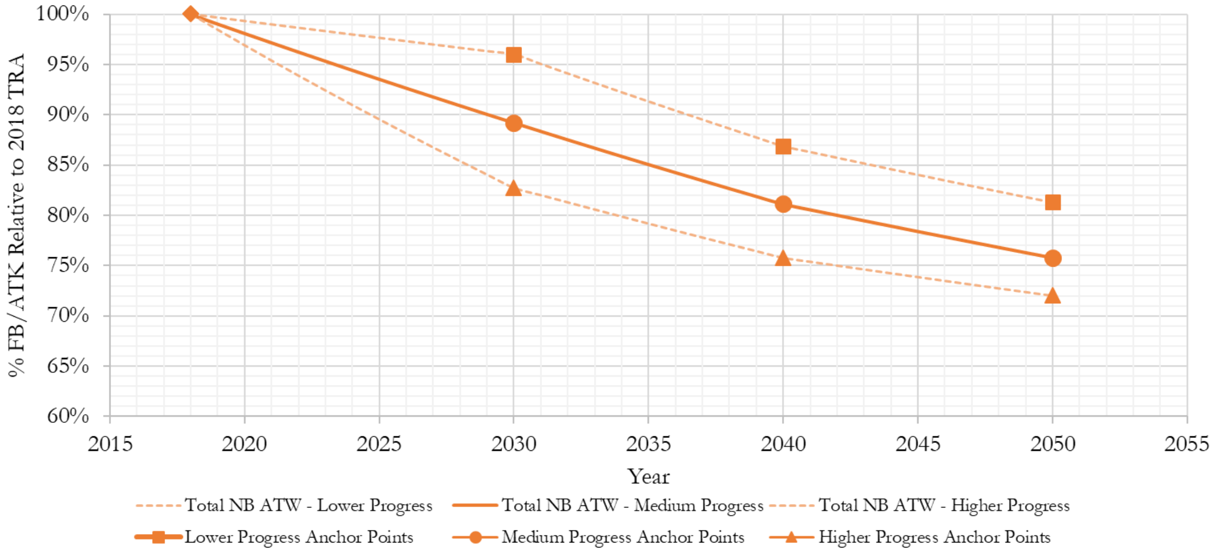


Figure 5-10. NB ATW FF/ATK Improvements Relative to the previous Decade

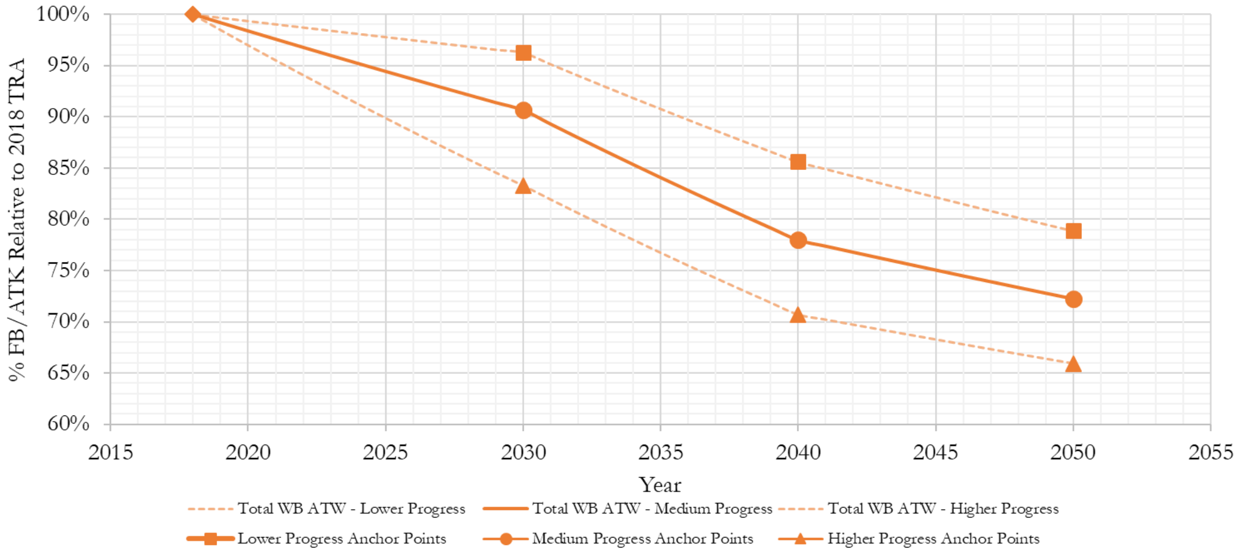


Figure 5-11. WB ATW FF/ATK Improvements Relative to the previous Decade

Finally, detailed data tables for each airframe have been compiled in Annex F. These tables show FB/ATK summaries for both design and R1 range, a mission performance summary, and detailed propulsion and airframe information. MDG prioritized the medium progress results for the fleet level analysis. The FB/ATK percentage savings relative to the 2018 TRAs for each aircraft and ATW for the “medium progress” confidence interval is depicted in Figure 5-12. In general, each ATW’s benefits reduce relative to the prior decade, with the WB providing the most reductions in 2050 of approximately 23% and the RJ the least with ~17% benefit. In the nearer term of 2030, the TP has more potential for improvements than the other classes due to the potential for more technological gains possible for that vehicle class, but tapers with time. The resulting ATWs in each time frame served as the basis for the possible ACAs that could potentially enter service in future years, as will be discussed in the following chapter.

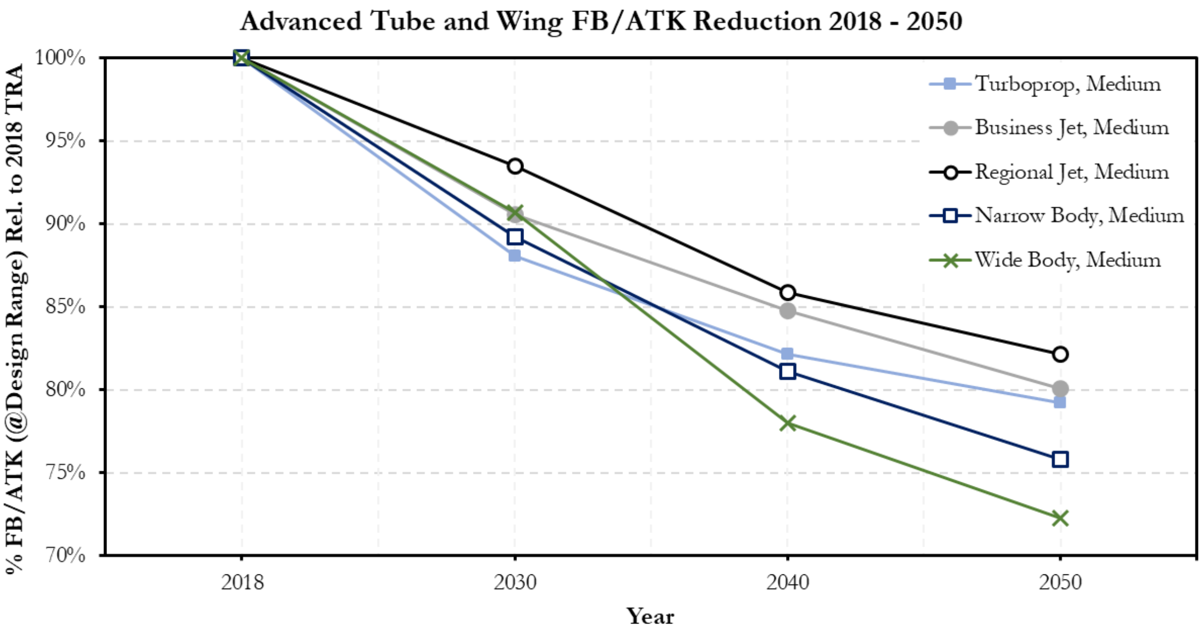


Figure 5-12. All ATW FB/ATK Improvements Relative to the previous Decade at the Medium Progress Level

APPENDIX M3.6. ADVANCED CONCEPT AIRCRAFT ASSESSMENT

6.1 INTRODUCTION

Previous chapters focused on the projected improvement of today's conventional configurations while noting the increasingly difficult challenges associated with improving highly optimized modern aircraft and engines. This chapter focuses on advanced concept aircraft (ACA) as potential pathways to additional fuel burn and carbon emission reduction with discussion on associated challenges of readiness, attainability, potential benefits, and interdependency with other factors such as reduction of noise and local pollutant emissions. Recall that an ACA differs from the ATWs in that an ACA includes an airframe, propulsion, energy and/or integrated vehicle architectural change from the TRA/ATW in a given aircraft category. The status of several ACAs was reviewed by IEs from 2017-19 as part of their review published in 2019 IEIR report. Unlike the current study, the scope of the IE Review was limited to entry into service horizons of 2027 and 2037 and did not consider the TP aircraft category. At that time opinions varied amongst the IEs as to the likelihood that any of these configurations could be in service by 2037, though no one disputed that there are significant technical and nontechnical challenges that would have to be overcome before a product launch.

The scope of the current study is broader, adding TP aircraft and with a longer time horizon. Additionally, a still-increasing sense of urgency to address climate change combined with an opportunity to build back greener as the world recovers from the global pandemic is leading to more R&D activity that should increase the possibility for step changes relative to that envisioned even a couple years ago. That being said, research and technology development and subsequent aircraft development and certification take time, so insertion of new aircraft, especially radically new ones, can only happen with considerable lead time. Throughout this report, as in the IE Report, a nominal timeline of 7 years from TRL6 to TRL8 is used, capturing the time from the point of aircraft product launch signifying confidence in commercial viability through aircraft and production system development and certification. Major derivative aircraft can take 1-2 years less, and history has shown that surprises along the way can extend any timeline. As shown in Figure 6-1, a commercially viable product opportunity requires many factors to come together – broadly a combination of readiness and attainability as used in the LTAG activity. It is clear that technical readiness is a necessary but not sufficient condition to realize in practice a new ATW or ACA. The realization of ACAs will require large-scale, costly demonstrations of critical technology elements (CTE) necessary to achieve sufficient confidence in commercial viability given the substantial change in architecture, as shown in Figure 6-2. Additionally, confidence in the use of non-drop-in fuel requires a confidence in the progressive deployment of necessary supporting infrastructure reaching sufficient levels and overall availability. But from the perspective of a business having confidence in the commercial viability of a new product, whether an ATW or an ACA, 7-years is a reasonable, often-used timeline.

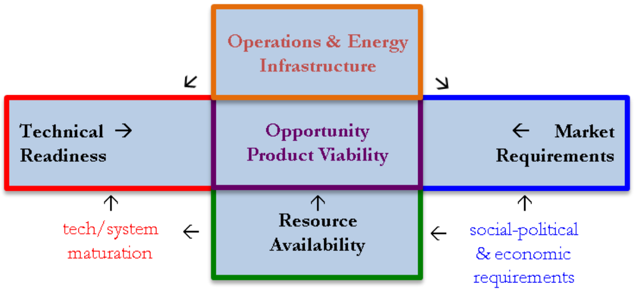


Figure 6-1. Commercial Viability - Many Dimensions Must Align to Realize a True Product Opportunity

This chapter summarizes a wide range of ACAs without identifying specific “winning” concepts. Through 2030, there is little doubt that new business and commercial transport aircraft entering service will remain as a conventional configuration with balanced improvement across all design objectives and meet market requirements. There is neither enough time nor planned investment to allow alternative concepts to reach TRL of 8 by 2030 for all but the smallest aircraft. Beyond 2030, it is likely that conventionally configured business and commercial transport aircraft will continue incremental improvement and remain the dominant configuration – this is characterized by LTAG-Tech scenario T1 that relies on progressively improving ATW configurations. But given the range of critical enabling technologies that enable step-changing ACAs, their current state of development and readiness, an increased sense of urgency relative to climate change and the time remaining to reach TRL of 8 for entry into service during 2030s, it is more than ever before within the realm of the possibility that an ACA could be developed and compete with or replace conventional configurations. This is not easy and is far from a certainty, but with today’s drivers and sufficient, timely investment, it is possible we could see change not so different from what we experienced 50-70 years ago with the emergence and convergence of swept wings and jet propulsion. These possibilities are represented in LTAG-Tech scenarios T2 and T3 allowing for alternative airframe and propulsion systems compatible with drop-in and non-drop-in energy sources, respectively, and with evolution occurring differently dependent on aircraft category.

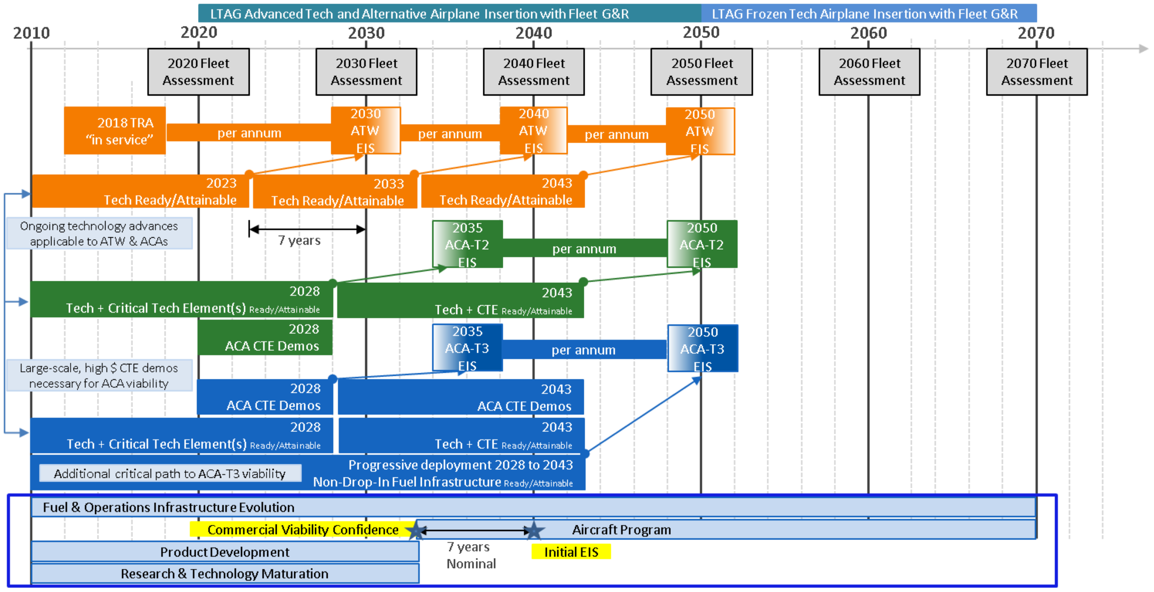


Figure 6-2. Aircraft Level Technology Impact Timing – Nominal: 7 Years for Commercially Viable Airplane Detailed Design/Development/Certification

Given the practical, real-world challenges to substantial change that are easily lost in the optimism of new technology research, the IEIR report (Chapter 9) included a discussion of barriers to change and the realities of aviation markets that is summarized as follows. Change is rarely as easy as it sounds or looks on paper. Aircraft are highly complex, integrated products of modern technology that provide value through unmatched capability to transport people and goods safely and economically at high speed over long ranges relative to other modes of transportation. Aircraft are performance guaranteed by OEMs to initial operators <u>before</u> detailed design, build, or certification. As indicated in Figure 6-2, the decision to offer a new product is a business decision made by business leaders in a complex, high technology marketplace, sometimes with a certain risk to a company's future existence. A new or derivative aircraft product decision is based on the convergence of technology readiness, market and regulatory requirements, resource availability and financial viability. Aircraft design itself is a subtle and complex balance of interdependencies and trade-offs that ends with no compromise to safety, sufficient economics for industry and operators, and mission capable performance that brings value to operators and society as the end users. Key aspects that must be fully addressed are elements of technology readiness including many so called "ilities," some of which are manufacturability, integrabililty, affordability, certifiability, reliability, sustainability, maintainability, operability, and stakeholder acceptability [20]**.** All these requirements are even more critical to fulfil for ACAs than for ATWs. If one dimension is missed, then there is no product opportunity.

For a truly disruptive technology or system concept, the uncertainty levels and lack of prior experience will very likely drive a necessary but not sufficient requirement for large-scale, integrated technology flight demonstration. The case where an alternative configuration itself is the disruptive "technology" will point to an X- or Y-plane type demonstration, as frequently used for military development programs. This is akin to Boeing's 367-80 in the 1950s that led to the Boeing 707. Such demonstrations require significant investment and associated risks on their own but are necessary to demonstrate benefits and readiness in the broadest sense before any business decision to launch a new product could be made. Looking back to the dawn of the jet age, several drivers of change are evident. First, the driver for a disruptive technological change was economic, although not necessarily driven by efficiency as maintenance costs drove the change from radial piston to jet engines. The second key enabler was substantial financial investment and acceptance of associated risk, which involved government investment to help industry explore beyond a risk threshold that they could reasonably pursue alone. Economics remains an inherent driver today, along with safety. Relative to disruptive change today, there is reason for optimism as we have a convergence of environmental challenges and the opportunity to recover greener from a global pandemic, both of which provide rationale for substantial government investment around the world to help innovate faster than industry could alone.

6.2 ACA ASSESSMENT METHODOLOGY

Due to time and resource constraints and because the inherent uncertainties of ACA development did not justify high efforts in overly precise models, the ACAs were not modeled quantitatively as with the ATWs and required a different methodology to be developed this assessment. The methodology adopted for the Tech SG is depicted in Figure 6-3 showing the following steps: (a) Configuration/ architecture screening based on potential benefits per scenario, (b) Technical and non-technical barrier identification, (c) Assessment of advanced aircraft concepts through scorecards, (d) Identification of representative aircraft for each class, (e) Vehicle level benefit quantification (compared to same-year ATW), (f) Technology and vehicle scenario-based projection (fleet penetration), and (g) Cost estimation and investment quantification.

The ACA assessment process starts with broad scanning of possible aircraft concepts, independent of current TRL, for a given vehicle category from ICAO Stocktaking, LTAG-TG members, and literature search using authoritative published reports from/for research organizations. Using these configuration options, a Morphological Matrix is created, representing all possible combinations of characteristics/attributes. Then, it is color-coded to determine which concepts would be seen under each of the three technology scenarios:

- **T1** – Advanced tube-and-wing
- **T2** – Advanced concept aircraft, drop-in-fuels

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[20] Yu, J. et al, "Total Technology Readiness Level: Accelerating Technology Readiness for Aircraft Design," AIAA Aviation Forum, AIAA-2021-2454, Virtual Event, 2 - 6 August 2021.

- **T3** – Advanced concept aircraft, non-drop-in fuels and energies

Recall that ACES specifically is not picking winners from the collection of ACAs; rather, the low, medium, and high benefits provided will be representative of the collection of concepts with consideration given to current state of study and projected readiness and attainability. Then, these concepts are mapped against the scenarios, and each configuration is qualitatively evaluated based on its potential benefit. The benefit information is used to represent a subset of most promising configurations to guide the remaining steps of the ACA assessment process.

The next step is to identify the technical and non-technical barriers of each representative aircraft configuration that is selected previously. These barriers can affect a wide variety of stakeholder groups inside and partly outside of aviation, including governments, Original Equipment Manufacturers (OEMs), airlines, airports, passengers, energy suppliers and so on. The importance of non-technological feasibility ("attainability") due to political, regulatory, economic, societal, infrastructural, and operational challenges will be magnified for advanced alternative concepts as they generally represent a significant change from today's accepted approaches and will require significant efforts from multiple stakeholders to be achieved.

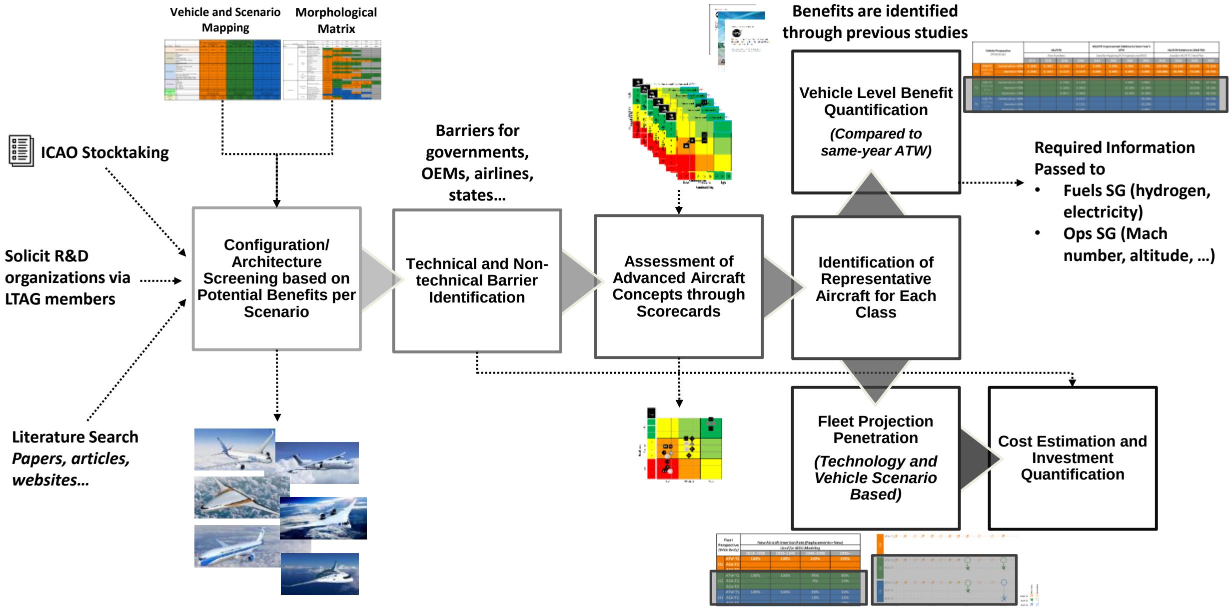

Figure 6-3. ACA Assessment Process Overview

In the third step of the process, scorecards are used to assess a range of ACAs side-by-side. The scorecard allows collection of Subject Matter Experts' (SMEs) perspectives on the readiness, attainability, and potential benefits of each aircraft concept for each technology scenario. Readiness is considered as the degree of achieving technical maturity including overcoming technical barriers, and the metric for readiness is Technology Readiness Level (TRL). SMEs are asked to consider the form, fit, and function of the ACA and its key enabling technologies, its current state of development and a cost-effective path to production and certification. In simple terms, the question being asked from a readiness perspective is: *Can the aircraft be physically created and be approved as safe with expected benefits?*

Attainability is treated as the ability to realize a commercially viable product overcoming non-technical barriers and the evaluation is performed in three areas: operability/system-of-systems infrastructure, stakeholder acceptability and economics.

Operability addresses the ability for day-to-day operations within the broader system of systems inclusive of reliability, sustainability, and maintainability to address relevant requirements and meet customer expectations for in service/operations within the air transport system at the time of entry into service and beyond. In addition, ACAs may require airport, airspace and energy supply infrastructure that is different from today's situation. In simple terms, the question asked of the SMEs in the scorecard is: *Is this aircraft concept consistent with the air transportation infrastructure and operational environment.*

Next, stakeholder acceptability is addressed and is representative of the motivation, willingness, and ability of financial investors, OEMs, regulators, operators, and the public to accept new aircraft concept or technology in all ways, given the perceived benefits and risks. In other words, SMEs are asked to answer this question: *Will the world accept this aircraft concept?*

The final aspect of attainability considers affordability addressing R&D from discovery through technology maturation and demonstration, airplane development through certification, airplane production costs, and airplane operational service life costs. It also considers shareholder economic risk acceptability. The SMEs are asked to evaluate the aircraft concepts qualitatively from cost perspective in the scorecards; quantitative estimates are performed by the Cost Estimation Ad-hoc Group. The question raised in this area is: *Can creating the aircraft concept and bringing it into cost-effective service be afforded considering the R&D investment (through TRL 6), airplane development through certification and initial EIS (TRL 6 to 8/9), and airline purchase and operations (TRL 9+)?* To complete the scorecard, the SMEs are asked to judge the potential benefits of the ACAs in terms of environmental aspects, i.e. energy efficiency, carbon intensity, noise and local air quality but also regarding operational aspects such as maintainability or airport turnaround time. Similar to attainability, there exists a pre-defined scale for benefits. Potential step-changes introduced via ACAs alternative architectures enabled by critical technology elements are judged against timewise progressively improved ATW conventional configurations. The entirety of the scenario information is then used to visualize how the concepts would develop over time under the scenarios in the context of the following questions: *Are the projected benefits worth the investment considering the risks?*

Next, using the readiness and attainability evaluations of the concepts collected through scorecards, two overlapping ACA "baskets" of innovation are identified beyond the ATW, with conventional or drop-in fuel: ACA T2 is representative of alternative architecture airframes and/or propulsion (with conventional or drop-in fuels), and ACA T3 is representative of advanced airframes and advanced propulsion characterized by the use of non-drop-in fuels and energies, mainly hydrogen or battery electric, with or without alternative airframe architecture changes. Note that an ATW configuration with non-drop-in fuels would also be considered as an ACA T3 alternative. As defined in section 2.4 Overall Tech SG Methodology, the qualifiers "T2" and "T3" indicate a system of three technology variations: T1 including ATWs only, T2 including ACAs without non-drop-in fuels and limited infrastructure change required, and T3 including all advanced aircraft including ACAs with and without non-drop-in fuels allowing for more major infrastructure change. Each group of aircraft were characterized as a whole, and that characterization is carried through the remaining steps of this methodology. In this manner, the potential benefits representative of a group of relevant concepts have been characterized without identifying or implying any single concept as a winner.

Vehicle-level benefit quantification of the representative aircraft is needed for the MDG fleet analysis. Since the advanced concepts are not modelled, the benefits are quantified by reference to authoritative studies previously performed by/for R&D organizations. In these studies, the advanced concepts are typically compared to baseline tube and wing configurations. The assumptions regarding the configurations are extracted from each study. With the help of Airframe and Propulsion Tahgs, the impacts of advanced configuration concepts are isolated from equivalent technology advanced conventional architecture configurations, and these impacts are applied to same-year ATWs. In this way, ACES has attempted to isolate the benefits and challenges associated with making a step change to an alternative architecture beyond an ATW. For each vehicle class, a range of energy intensity change, i.e. change in energy consumption per unit of transport (MJ/ATK), representing low to moderate and high progress relative to the same year ATW was estimated and documented.

For the modeling of the ACAs in the fleet by MDG, proxy aircraft within each aircraft category were needed, which would represent the basis of change of the ACA energy intensities. For example, in the narrow body class, ACA T2 and ACA T3 were represented as an improvement from the NB TRA (notional A320-neo) and its improved versions over the years. Some ACAs have a lower range capability than the corresponding reference aircraft. Whenever necessary, that was also provided to the fleet evolution modelers. It should be noted that direct comparisons across reports and concepts is generally difficult as baselines and future technology assumptions including timeframes vary across the literature, thus the characterization across a group of concepts requires some level of expert qualitative assessment to effectively normalize the differences. The figures of merit for each ACA class were in terms of MJ/ATK to capture the energy intensity independent of the type of fuel used – so an energy-use-based metric relative to a same year ATW. To obtain the impact on CO_2 emissions, this energy metric is then combined with the lifecycle emissions factor provided by the Fuels SG.

Next, the aircraft market share (production/introduction) projections of ACAs vs ATWs was made for 2018-2070, with the extra 20 years of fleet assessment being included to realize potential reductions from the new technologies, which would be introduced in 2050. This is further discussed in the following Chapter.

6.3 GENERAL TRENDS AND CONCEPTS

Research and development into alternative aircraft and propulsion system architectures continues around the world. The increasing focus on combatting climate change is a strong motivation to reinforce the efforts to find more sustainable solutions for future aviation and to overcome all the known and potentially unknown barriers to change. Today more than ever, there is reason for optimism to achieve disruptive change, as we have a convergence of environmental challenges and the opportunity to recover greener from a global pandemic. Previous chapters focus on advanced technologies as applied to advanced conventional configurations, with several having the potential to introduce a step change and shift curves off historical trends. Many of these technologies are already buying their way on aircraft incrementally. These technologies are generally applicable to alternative configuration concepts as well. The question for this section is what are alternative architectures that enable step changes to new levels of performance beyond that projected for conventional configurations, and when are they projected to be technically ready and overall attainable. The assumption herein is that under some but not all scenarios, alternative architectures will be realized between now and 2050. Most likely solutions have to be filtered out from the many suggested and studied in the recent past. The Venn diagram in Figure 6-4 provides a framework to generalize the alternative architecture possibilities into categories of airframe, propulsion, energy systems on the aircraft that must all fully integrate to have a viable solution. Brief descriptions of the major concepts are given below with detailed information found in supporting references.

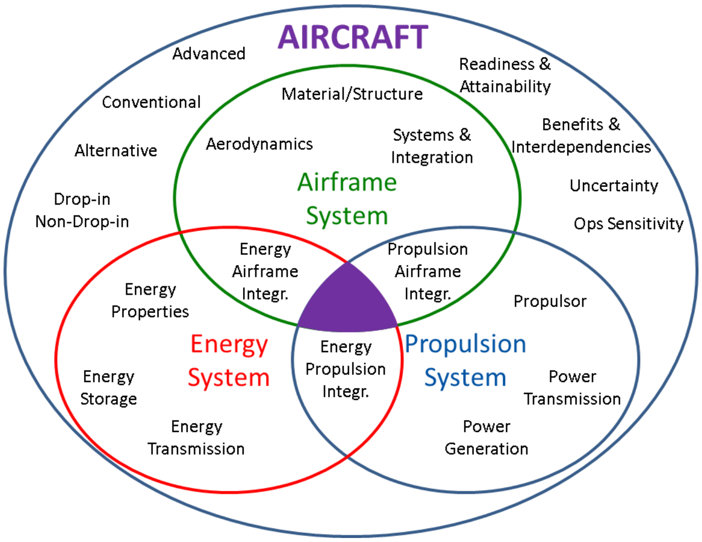

Figure 6-4. Generalized Alternative Architecture Possibilities

6.3.1 Alternative Airframes

6.3.1.1 Hybrid Wing-Body

The hybrid wing-body (HWB) aircraft class has no clear external dividing line between the wings and the main body of the aircraft external surfaces. Internally, it is composed of distinct wing and body structures. HWB configurations may or may not be tailless, and generally install the propulsion system on the upper surface, which also enables noise reduction through acoustic shielding. The HWB shape effectively blends volumetric and wetted area advantages for aerodynamic efficiency benefits and though often sized to fit existing airport gate constraints, tends to fully optimize performance with a larger span that would benefit from folding wing tip technology. The cross-sectional area distribution can be nearly ideal for low transonic drag, and the more uniform distribution of loads provides structural weight benefits.

Several HWB configuration design variants have been developed including the Boeing Blended Wing Body (BWB) [21, 22] concept with over-the-body pylon-mounted nacelles, the Lockheed Martin Hybrid Wing Body (HWB) [23] concept with tail and over-wing pylon-mounted nacelles, and the DZYNE tailless BWB concept with flush-mounted nacelles and boundary-layer diverter in front of the inlets. Airbus includes a BWB configuration as one of three hydrogen-powered study aircraft in its ZEROe [24] program. Figure 6-5 shows the Boeing BWB concept on the left, Lockheed Martin concept in the middle, and the Airbus ZeroE concept on the right. A recent review of HWB research around the world is found in the paper

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21 Liebeck, R.H., "Design of the Blended Wing Body Subsonic Transport," AIAA Journal of Aircraft, Vol. 41, No. 1, January-February 2004, p. 10-25. https://arc.aiaa.org/doi/pdfplus/10.2514/1.9084

22 Bonet, J. T., "Blended Wing Body Transport Aircraft Research & Development," 31st ICAS, ICAS2018-0298, 9-14 September 2018. https://www.icas.org/ICAS_ARCHIVE/ICAS2018/data/papers/ICAS2018_0298_paper.pdf

23 Hooker, J.R., Wick, A.T., Hardin, C.J., "Commercial Cargo Derivative Study of the Advanced Hybrid Wing Body Configuration with Over-Wing Engine Nacelles," NASA CR-2017-219653, November 2017. https://ntrs.nasa.gov/api/citations/20170011487/downloads/20170011487.pdf.

24 Airbus, "ZEROe: Towards the world's first zero-emission commercial aircraft," retrieved 29 September 2021. https://www.airbus.com/innovation/zero-emission/hydrogen/zeroe.html.

by Zhenli et al [25]. The HWB concepts have typically focused on WB aircraft missions including freighters but the DZYNE concept introduced a new landing gear concept that may enable an efficient single deck design that could open the applicability of HWB to NB, RJ, and BJ aircraft.

Figure 6-5. Representative HWB variants

The most developed HWB concepts are at a state of readiness requiring large-scale transonic demonstration to reach TRL6. Though many key technical barriers have been addressed, significant uncertainties around manufacturing, family concept implementation, passenger ride quality, unique certification processes and challenges (e.g. certifiable emergency exits from vehicle), and airport operations present risks in the minds of many. Possible entry into service is estimated in the 2035-40 timeframe with energy reduction estimated in the 5-15% range relative to same year ATWs [26, 27].

6.3.1.2 Truss/Strut-Braced and Boxed/Joined Wings

Alternative wing architectures on otherwise mostly conventional fuselages are another category of ACA, as depicted in Figure 6-6. Truss and/or strut-braced wing technology has been studied for two decades and are currently applied to some lower-speed (smaller) aircraft; the revolution here is the efficient application at typical transonic speeds. The structurally braced wing can enable a substantial span increase without the typical weight penalty through coupled aero-structural design, thereby reducing induced drag to yield a net fuel burn benefit. Given the large span, it will require folding wingtips to meet existing gate constraints.

The relatively short chords and lower sweep are more compatible than current aircraft with natural laminar flow design but provide added technical challenges in thin wing actuation and system integration. The boxed/joined wing concept similarly targets induced drag reduction through joining two horizontally offset wings at the tip and avoids the need for folding tips. The large span and small chords may challenge high-lift integration and ice-protection requirements.

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[25] Zhenli C., et al, “Assessment on critical technologies for conceptual design of blended-wing-body civil aircraft,” Chinese Journal of Aeronautics, Volume 32, Issue 8, 2019, Pages 1797-1827, ISSN 1000-9361, https://www.sciencedirect.com/science/article/pii/S1000936119302493

[26] Nickol, C. L., Haller W. J., “Assessment of the Performance Potential of Advanced Subsonic Transport Concepts for NASA’a Environmentally Responsible Aviation Project,” AIAA-2016-1030, 4-8 January 2016 https://arc.aiaa.org/doi/10.2514/6.2016-1030

[27] Mavris D. N., Schutte J. S., “Application of Deterministic and Probabilistic System Design Methods and Enhancements of Conceptual Design Tools for ERA Project”, NASA/CR-2016-219201, May 2016. https://ntrs.nasa.gov/citations/20160007420

The truss-braced technology has been studied on several transonic transport aircraft concepts since 2008 [28, 29, 30, 31] and has led to focused research with key tests to address the most significant uncertainties and refine design benefits; most development focus has been in the NB category, but applicability to RJ and WB has also been studied. Interest in the boxed wing concept has revived more recently [32, 33] with focus in the NB to WB seat classes and RJ/NB speeds.

The configuration of the truss/strut or boxed/joined wing provides ample room to integrate future large diameter turbofan engines as well for additional benefits. Figure 6-6 shows an example of both truss-bracing (Boeing SUGAR concept) and a boxed wing (EU Parsifal project) concept. These wing architecture changes are viewed as less radical than the HWB concepts and therefore as more attainable, though not without further development to include a large-scale aero-elastic flight test at high-speed. The readiness of the truss technology is estimated to be higher than the boxed technology today, but both will require a large-scale transonic demonstration to achieve TRL6. Possible entry into service is estimated in the 2035 timeframe with energy reduction (exclusive of any enabled propulsion benefit) estimated in the 5-10% range relative to same year ATWs.

Figure 6-6. Representative braced (left) and boxed (right) wing configurations

6.3.1.3 Novel Fuselages

Another path of potential airframe change focuses on the fuselage where there is ongoing research ranging noncircular lifting fuselages [34, 35] to the relatively new "flying-V" concept [36]; Figure 6-7 shows examples. Approaches that fit in this category range from relatively small derivatives of ATW technologies to more dramatic change that often combined with or a variant of other revolutionary changes, such a blending or novel propulsion airframe integration approaches. The ACA-relevant approaches are

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28 Bradley, M.K., Droney, C.K., Allen, T.J, "Subsonic Ultra Green Aircraft Research: Phase II – Volume I – Truss Braced Wing Design Exploration," NASA CR-2015-218704, April 2015

29 Droney, K. C., et al., "Subsonic Ultra Green Aircraft Research: Phase III – Mach 0.75 Transonic Truss-Braced Wing Design," NASA/CR–20205005698, September 2020.

30 Harrison, N. A., et al., "Development of an Efficient M=0.80 Transonic Truss-Braced Wing Aircraft," AIAA Scitech 2020 Forum, AIAA-2020-0011, 6-10 January 2020. https://arc.aiaa.org/doi/10.2514/6.2020-0011

31 Chau, T., Zingg, D. W., "Aerodynamic Optimization of a Transonic Strut-Braced-Wing Regional Aircraft Based on the Reynolds-Averaged Navier-Stokes Equations," AIAA 2021-2526, August 2021. https://arc.aiaa.org/doi/abs/10.2514/6.2021-2526

32 Cipolla, V., et al., "Preliminary design and performance analysis of a box-wing transport aircraft," AIAA Scitech 2020 Forum, AIAA 2020-0267, 6-10 January 2020. https://arc.aiaa.org/doi/10.2514/6.2020-0267

33 PARSIFAL: Prandtl Plane Architecture for the Sustainable Improvement of Future Airplanes, retrieved 8 October 2021. https://parsifalproject.eu/

34 Yutko, B., et al., "Conceptual Design of a D8 Commercial Aircraft," AIAA Aviation 2017 Forum, AIAA 2017-3590, 5-7 June 2017. https://arc.aiaa.org/doi/10.2514/6.2017-3590

35 JAXA Aeronautical Technology Directorate, "Eco-wing technology," retrieved 5 October 2021. http://www.aero.jaxa.jp/eng/research/ecat/ecowing/)

36 Oosterom, Wilco, "Flying-V Family Design," Master's Thesis – TU Delft Aerospace Engineering, retrieved 7 October 2021.https://repository.tudelft.nl/islandora/object/uuid:9e8f9a41-8830-405d-8676-c46bf6b07891?collection=education

estimated to be attainable in the 2040s with significant development required before a large-scale transonic demonstration. Depending on the approach, isolated benefits could range from 5% or lower for less complex change to 10 to 15% for those that are effectively HWB/BWB derivatives, although with much higher uncertainty today. Applications range from RJ to NB and WB.

Figure 6-7. Representative novel fuselage concepts

6.3.1.4 Novel Propulsion Airframe Integration

Many ACA configurations under study around the world leverage novel propulsion airframe integration (PAI) at the configuration level. This topic is discussed here as revolutionary changes are important and obvious by observation of the external configuration, though most concepts also at least equally rely on challenging propulsion system advances and PAI under the skin as well. In reality the HWB concepts generally move away from conventional PAI, while the advanced wing concepts typically incorporate more conventional PAI. The most prevalent and significant alternative PAI approaches include the concepts of boundary-layer ingesting (BLI) and distributed propulsion (DP). Concepts with BLI and/or DP are not new, and the principles are understood as ways to improve propulsive efficiency, with additional potential benefits of BLI to reduce drag though less wetted area for nacelles. But by their nature, each of these concepts is highly sensitive to installation drag externally and internal propulsion system losses not the least of which is due to distorted/nonuniform inlet flow for BLI and efficient power transmission for DP. The IEIR report provides a wide range of aircraft concepts (repeated herein as Figure 6-8), describes fundamental differences between installations causing 180- or 360-degree fan distortion fields, describes remaining technical challenges and interdependencies, and provides a range of fuel burn estimates. There is research that studies applications across the range of aircraft categories. Given the remaining technical challenges and complexity of integration, potential entry into to service is estimated beyond the next generation of aircraft beyond 2040 at the earliest, apart from DP applied to small aircraft which could appear sooner. Further technical development and system study is needed that will eventually lead to the need for large-scale demonstration at speeds relevant to a target aircraft category. Potential benefits are dependent on the mission and application but are estimated to range from a few percent to approaching 10% in the far term.

Figure 6-8. Representative ACAs incorporating BLI (IEIR report, figure 9-5)

6.3.2 Alternative Propulsion and Energy

6.3.2.1 Unducted Fans

Beyond turboprops, the advanced conventional propulsors are ducted. A revolutionary alternative is the unducted fan (UDF) – with higher loading and cruise speeds than with propellers. It is also referred to as open rotor and has enabled high by-pass ratio beyond what is possible with ducted turbofans. The counter rotating open rotor (CROR) propulsor concept has been studied in Europe and the US for decades, with surges in research and development aligning with high fuel prices, and less interest when fuel prices are low. More recently and since completion of the IEIR report, technology demonstration plans for a new single-stage concept have been announced by CFM [37] (see Figure 6-9) as part of its integrated Revolutionary Innovation for Sustainable Engines (RISE) program. In the EU Clean Sky research project, the CROR propulsion system has been shown to be capable of providing fuel burn improvement over turbofans engines for short- to medium range aircraft at a negligible speed penalty.

The cruise speeds possible are in the Mach 0.75-0.80 range, typical of today's RJ- and NB-class aircraft. The EU Clean Sky program led up to a ground test demonstrator campaign by Safran in 2017/2018. Results presented to the IEs show potential fuel burn savings for CROR of about 5% (+/-2%) below advanced turbofans at same date of 2037. Noting that noise of UDF has been a significant hindrance to attainability, recent results have given confidence in the ability to be community noise compliant to Chapter 14 with some margin. Recent research in the US, culminating in acoustic wind tunnel tests, showed similar results; specifically, cumulative noise levels for the CROR which were 8-10 EPNdB below Chapter 14 noise limits, with advanced ducted fans about a further 7 EPNdB quieter. However, in both European and US studies, the potential benefits are subject to significant uncertainty and critical challenges, including blade-off containment, installation and cabin noise treatment that will all lead to a weight penalty on the aircraft in comparison to an equivalent technology level under-wing ducted-fan configuration. From an attainability standpoint, it is not certain that the acoustic margin versus the Chapter 14 noise regulation will be judged sufficient by the customers, as compared to the quieter ducted fan systems, in view of potential future noise certification stringency increase and individual airport regulations. The single-stage concept recently announced should reduce some of the technical risks and the announcement of the flight demonstration contributes to confidence in timing and investment. So, while the IEIR report (chapter 9) evaluated the

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[37] Aviation Today, "GE Aviation & Safran See Sustainability as Key for Next-Gen VFM Engine," retrieved October 6, 2021. https://www.aviationtoday.com/2021/06/21/ge-aviation-safran-see-sustainability-key-next-gen-cfm-engine/

CROR and characterized the concept as an alternative not possible by 2037; today, the estimated readiness and attainability is estimated to be by 2035 and applicable to RJ and NB class aircraft.

Figure 6-9. CFM UDF rendering – not representative of any defined future aircraft configuration [37]

6.3.2.2 Electrified Aircraft Propulsion

The possibility of electrified aircraft propulsion (EAP) has emerged over the last decade with potential applications envisioned across every air vehicle imaginable from small vertical take-off/landing aircraft to the largest of transports in one form or another. The interest is supported by a perceived relative ease of electrical versus mechanical distribution of power around the aircraft along with maintenance benefits. There is a range of EAP systems inclusive of all-electric, hybrid-electric, partially turboelectric, and turboelectric architectures [38]. From a configuration standpoint, the possibility of decoupling energy source/power generation from a propulsor, or a having a single energy source/power generator driving multiple distributed propulsors, is attractive. From an emissions standpoint, the potential impact is strong but is highly dependent on both the system architecture selected and the source/mix of energy used onboard. Taking a lifecycle view, an electric system could provide carbon-free emissions if charged on a renewable grid but could easily have higher carbon emissions than jet fuel if charged on today's grids in many countries.

A hybrid or turboelectric system brings conventional (or SAF) jet fuel onboard as part or all of the energy supply and impacts the emissions. Broadly speaking, key challenges of EAP center on weight (low gravimetric energy and power density of battery storage systems and high weight of many components), altitude effects, development of new certification rules for power-electric systems, and access to electric power at airports sufficient for future large fleets. Additionally, it is common to report emission savings through reduced fuel consumption, but in reality, it is critical to report the energy savings and the energy mix in order to understand the lifecycle missions in the electrified world. Because electric grids are changing and variable around the world, care must be taken to understand that quoted emissions have both location and time dependency as well considering today's primary energy mix for electric power production is quite emissions-intensive in many world regions, but is undergoing a gradual transition to more renewable energy worldwide. Introducing electric aircraft in the near future may therefore deliver significant emissions reductions only in later years once more renewable electricity is available, or if operators select specific renewable electricity purchase contracts.

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[38] National Academies of Sciences, Engineering, and Medicine, "Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions," 2016, Washington DC: The National Academies Press. DOI:10.17226/23490

EAP-related research and development activities are rapidly expanding around the world, including ground and flight tests from the component to airplane level [39, 40, 41]. In Figure 6-10, a wide range of concepts and projects are presented and characterized by degree of hybridization in terms of block energy and power from all-electric to turboelectric concepts – note that within the reference paper [42] depicted in Figure 6-10, there are references to each of the concepts shown. There are already all-electric commuter class aircraft flying today and as technology improves with time and investment, so will the application to larger and/or longer-range aircraft. While the small, all-electric or initial hybrid-electric aircraft maybe in service prior to 2030 or 2035 and be important steppingstones towards increasingly larger aircraft, for the purposes of LTAG it is estimated the initial service for TP, RJ, and NB would occur by 2035, and by 2050 for WB. In this timeframe, it is estimated that initial applications will be of a hybrid architecture [43, 44]. The energy density of batteries and system power density of components are the key technology factors limiting all-electric aircraft to the smallest sizes where impact on global emissions is small. The energy density of batteries today is approximately 2 orders of magnitude lower than jet fuel [45] and while gradually improving, the probability of a breakthrough significant enough to enable commercially viable all-electric large TP, RJ, NB, or WB aircraft through 2050 is very low.

Mild hybrid electric propulsion systems where the battery is used to supply a relatively small amount of power could also be adopted with little impact on infrastructure and could potentially enable a 3-5% energy benefit to RJ and NB by 2035; note many concepts charge the battery during flight with relatively little charging at ground stations. As the vehicle size reduces and energy requirement drops, hybrid systems with batteries as more substantial secondary energy storage could become more viable. Such a trend is also depicted in Figure 6-10. A 5-20% fuel burn reduction could be achieved at a reduced range for a regional size hybrid electric TP by the 2035 timeframe and with a commuter size earlier than that. However, all-electric propulsion systems are not likely by the same timeframe, and hybrid systems will remain heavily dependent on conventional fuels or SAF and less so on ground charging systems for the RJ and larger aircraft.

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39 Clean Sky, “Green Regional Aircraft (GRA),” retrieved October 7, 2021. https://www.cleansky.eu/green-regional-aircraft-gra

40 Central Institute of Aviation Motors, “Russia continues tests of flying testbed with superconducting electric aircraft engine”, retrieved October 6, 2021. https://ciam.ru/en/press-center/news/russia-continues-tests-of-hybrid-flying-laboratory-with-superconducting-electric-aircraft-engine/

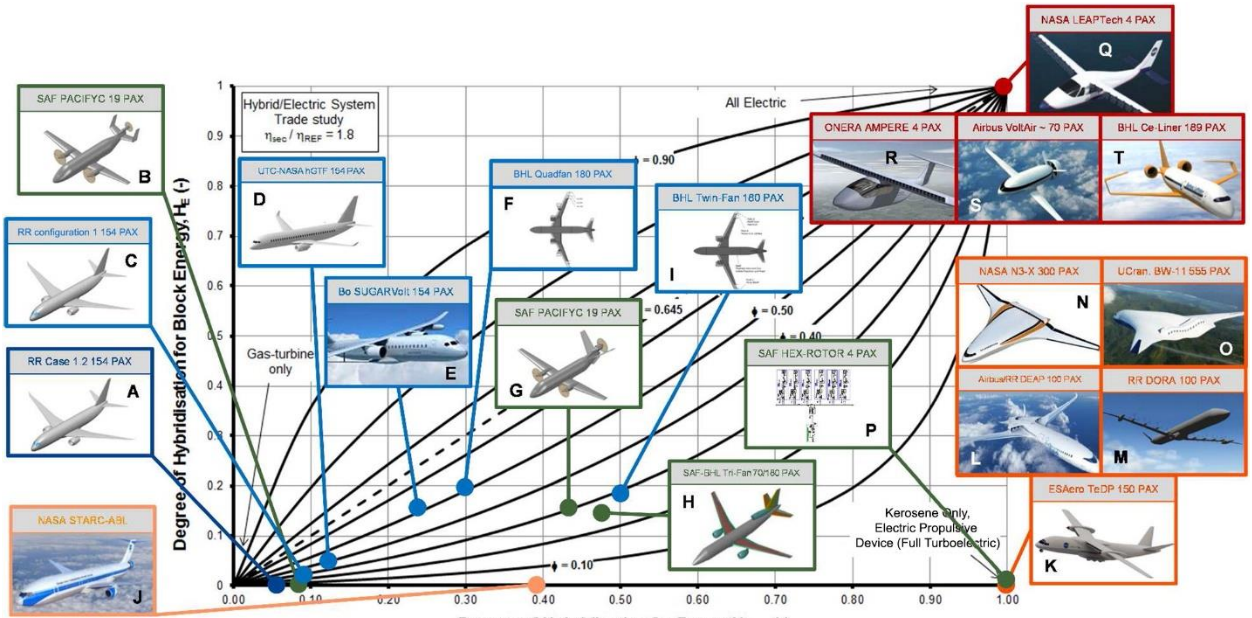
41 NASA, “NASA Issues Contracts to Mature Electrified Aircraft Propulsion Technologies,” retrieved October 6, 2021. https://www.nasa.gov/press-release/nasa-issues-contracts-to-mature-electrified-aircraft-propulsion-technologies

42 Isikveren A. T., “Progress in Hybrid/Electric Transport Aircraft Design,” 2017 More Electric Aircraft, Bordeaux, France, Feb. 2017. https://www.see.asso.fr/en/e-see1/eventbyyear/all

43 Bertrand, P., et al., “Parallel Hybrid Propulsion System for a Regional Turboprop: Conceptual Design and Benefits Analysis,” AIAA 2019-4466, AIAA Propulsion and Energy 2019 Forum, 19-22 August 2019. https://arc.aiaa.org/doi/10.2514/6.2019-4466

44 Lents, C. E., Baig, Z., “Parallel Hybrid Propulsion & Secondary Power System Architecture Exploration and Evaluation,” AIAA 2020-3555, AIAA Propulsion and Energy 2020 Forum, 24-28 August 2020. https://arc.aiaa.org/doi/10.2514/6.2020-3555

45 Langford, J.S. and Hall, D.K., “Electrified Aircraft Propulsion,” The Bridge, National Academy of Engineering, Vol. 50, NO. 2, Summer 2020, p 21-27. https://www.nae.edu/File.aspx?id=234402



References corresponding to annotations: A [16], B [17,18], C [16], D [19], E [20–22], F [23], G [17,18], H [11], I [24], J[25], K [26], L [27], M [28], N [29], O [30], P [18], Q [31], R [32], S [33], T [34]

Figure 6-10. International studies related to electrified aircraft [42]

6.3.2.3 Hydrogen

Hydrogen is a theoretically unlimited energy carrier and has been periodically studied as an aviation fuel over the last century thanks to its low specific weight and high gravimetric energy density. Initially hydrogen-powered aircraft were studied early in the jet age primarily for military purposes, then in the 1970s with NASA-sponsored studies on liquid hydrogen (LH2) fueled long-haul subsonic transports, and the late 1980s saw the flight demonstration of a modified Tu-155 aircraft. Interest spiked again around the turn of the century with multiple, comprehensive LH2-fueled aircraft system studies, for example the European Cryoplane project. In the few years since the IEIR report published in 2019, interest in the potential of hydrogen-based aircraft has risen dramatically with the worldwide focus on decarbonization and the potential of hydrogen as a carbon-free fuel from tank-to-wake leading to heightened levels of research and development including activities ranging from flying demonstrations of small aircraft to detailed concept studies of larger aircraft, plus an unprecedented level of study beyond the aircraft technology on topics ranging from production and delivery to storage and operations at the airport.

The driver is the potential use of a zero-carbon fuel as a tank-to-wake solution addressing the challenge of aviation decarbonization and impact on climate change. Several overview studies have been released that address the full lifecycle challenges of hydrogen [46, 47, 48, 49] and include some information on aircraft technology of direct interest to the ACES Tahg. Note that the LTAG-Fuels Group has addressed the well-to-tank portion of the energy challenge, inclusive but not limited to the challenges of cost-effective production of green hydrogen and delivery/storage around the globe – these types of challenges related to infrastructure have been and remain major barriers to the attainability of hydrogen powered aircraft. Today's global drive towards sustainability economy wide gives hope that over the next several decades these barriers can be reduced or eliminated and forms the basis for ACES to consider such aircraft in technology scenario T3.

From a technology standpoint, hydrogen can be used as a fuel in two ways. First, in direct combustion replacing jet fuel, and second, in fuels cells as a source of electrical power. Relative to jet fuel, hydrogen is about three times lighter per unit energy, but requires about four times more volume per unit energy, all of which contributes to a different set of design and mission performance trades relative to aircraft with conventional or drop-in energy. Certification of new, unconventional systems, including cryogenic storage, onboard delivery, and thermal management, as safe for commercial operations present a range of challenges and uncertainties. Safety risks of hydrogen are noticeably different from those of conventional fuels, and its public perception widely varies [50], which dictates another attainability challenge relative to stakeholder acceptability. The use of large-scale demonstrations for performance, within vehicle and system of systems integration, and safety will be required and are starting on scale aircraft.

In reviewing how hydrogen may enter aviation as a fuel, Figure 6-11 from Cranfield University presents a likely pathway that grows from small, shorter-range fuel-cell based electric or hybrid electric aircraft and eventually to the larger, long-range aircraft that are more likely to use liquid hydrogen in combustion; noting that GT in this figure implies gas turbines. The concepts under study in the Airbus ZEROe program bridge this range with the expressed plan to down select to a concept in 2025 and develop it further for EIS by 2035. There are a range of ongoing technology development activities with demonstrators at the small, short-range end of spectrum that are developing much knowledge and experience that can be applied to the large aircraft later; it is possible several of the smaller, commuter sized aircraft reach limited commercial service by 2030. The Cranfield University team also presented a series of innovation waves for larger aircraft as shown in Figure 6-12. Here one sees the impact of the volume requirement associated with hydrogen has on aircraft design and a likely stepwise evolution that eventually leads to alternative airframes characterized by adding volume. Initially, at least, the added volume has the impact of replacing payload and/or increasing structural weight and drag and in turn the mission energy requirement. Herein lies the trade that impacts the mission range and energy efficiency. In the farther term, concepts such as the HWB/BWB appear to have some natural synergy with hydrogen volume requirements and increasing airframe efficiency.

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[46] McKinsey & Company, "Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050," May 2020, https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf

[47] NLR and SEO, "Destination 2050: A Route to Net Zero European Aviation," February 2021, https://www.destination2050.eu/wp-content/uploads/2021/02/Destination2050_Report.pdf

[48] Bruce S., Temminghoff M., Hayward J., Palfreyman D., Munnings C., Burke N., Creasey S., "Opportunities for hydrogen in aviation," 2020, CSIRO.

[49] Airports Council International and Aerospace Technology Institute, "Integration of Hydrogen Aircraft into the Air Transport System: An Airport Operations and Infrastructure Review," 2021. https://store.aci.aero/product/integration-of-hydrogen-aircraft-into-the-air-transport-system-an-airports-operations-and-infrastructure-review/

[50] IATA fact sheet: https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet7-hydrogen-fact-sheet_072020.pdf

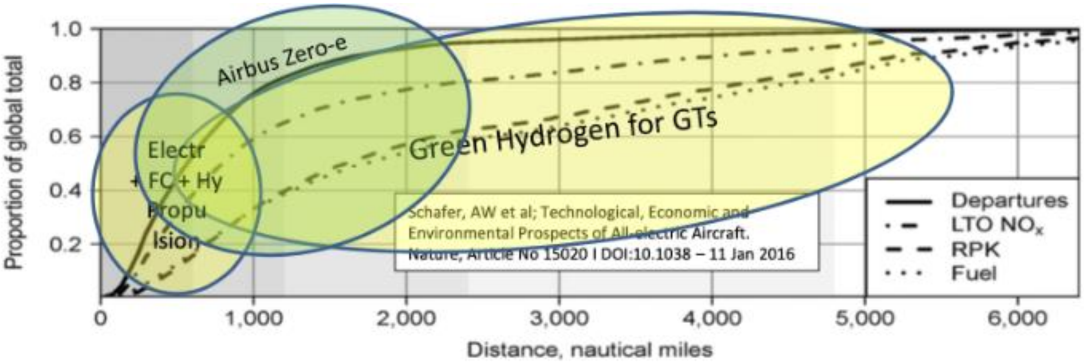
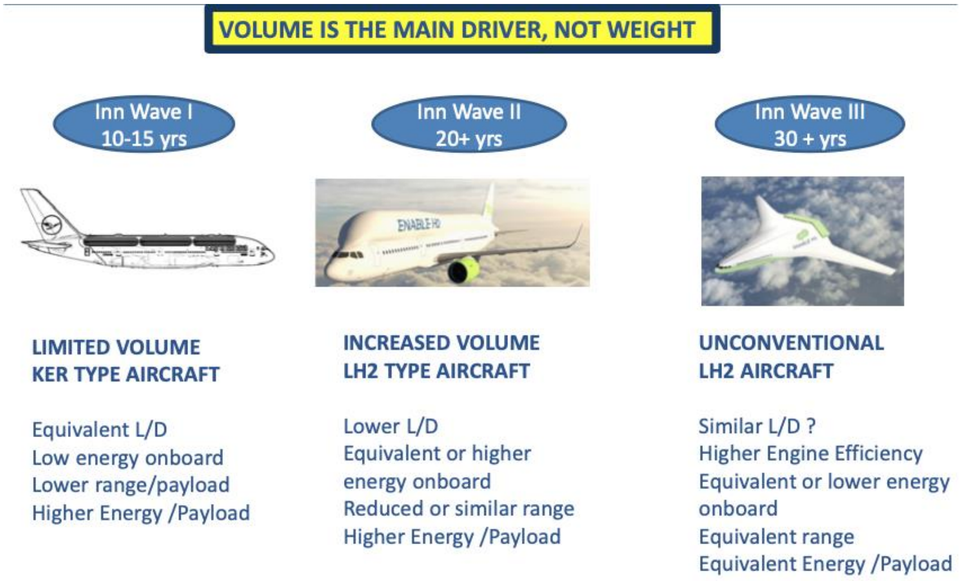


Figure 6-11. Potential Innovation Waves for Decarbonization Using Hydrogen. Presented by the Cranfield University ENABLE-H2 team to LTAG-Tech/ACES, April 2021.



VOLUME IS THE MAIN DRIVER, NOT WEIGHT

Inn Wave I 10-15 yrs	Inn Wave II 20+ yrs	Inn Wave III 30 + yrs
LIMITED VOLUME KER TYPE AIRCRAFT	INCREASED VOLUME LH2 TYPE AIRCRAFT	UNCONVENTIONAL LH2 AIRCRAFT
Equivalent L/D Low energy onboard Lower range/payload Higher Energy /Payload	Lower L/D Equivalent or higher energy onboard Reduced or similar range Higher Energy /Payload	Similar L/D ? Higher Engine Efficiency Equivalent or lower energy onboard Equivalent range Equivalent Energy /Payload

Figure 6-12. Potential Innovation Waves relative to Vehicle Performance. Presented by the Cranfield University ENABLE-H2 team to LTAG-Tech/ACES, April 2021.

The authoritative literature has many design studies for LH2 aircraft. The range of trades is large as are the range of technology assumptions at various time horizons. So, the range of energy intensity possible is wide and varied from many concepts where energy use increases dramatically and/or useful ranges reduced to some that foresee energy efficiency improvement, particularly as aircraft size increases and the gravimetric efficiency of onboard tanks becomes more favorable at constant technology levels. Figure 6-13 from Verstraete [51] studied several seat-classes and compared the efficiency of hydrogen against kerosene fueled aircraft as function of range. The figure shows a compromise of range capability for use of hydrogen at the NB sizes, and distinct crossover points that indicate hydrogen aircraft have better range capability at the large/longer-range WB sizes. The specifics of any product design, of course, will consider many unique

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[51] Verstraete, D., "On the energy efficiency of hydrogen-fueled transport aircraft", 2015. https://www.sciencedirect.com/science/article/pii/S036031991500943X

design requirements and make many distinct trades. Given the current level of technical activity including small aircraft demonstrations combined with heightened motivation around the world, ACES estimated under scenario T3 by 2035 we could see TP, RJ, and/or NB hydrogen combustion or hydrogen fuel-cell based aircraft enter service. The TP would more likely be fuel-cell based and the RJ/NB combustion based, but each would be range limited relative to the same year ATW and likely have lower energy efficiency. It was estimated that the technology applied to the BJ category would lag to 2040 and incorporate hydrogen via a fuel-flexible system that would not eliminate the use of drop-in fuel on the same aircraft. The WB is estimated to lag further out to 2050 but given the time and potential efficiency gains with increased size/range, it has the best chance for synergy between mission range, energy use, and carbon intensity.

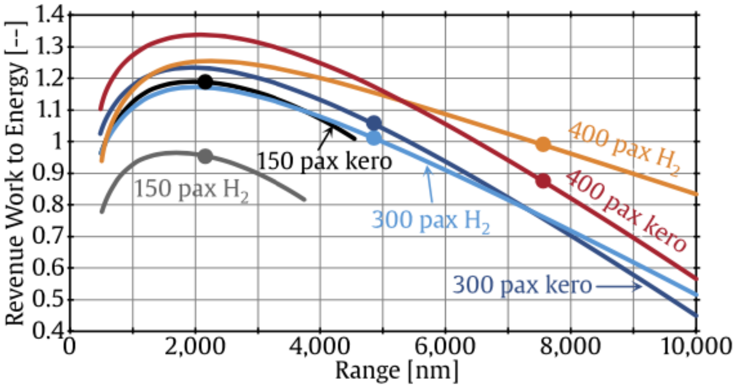

Figure 6-13. Variation of Energy Efficiency with Range for Hydrogen- and Kerosene-Fueled Aircraft

So, hydrogen-based aircraft are possible in the LTAG time horizon. There are technical challenges and broader attainability challenges. The technical challenges associated with hydrogen aircraft, while significant, appear to be smaller barriers to overcome than associated infrastructure requirements. Business model changes may be required of operators and accepted by customers that are associated with reduced ranges and reductions in non-stops flights. And aircraft owners, be they operators or leasers may have to accept less asset range flexibility. Additionally, it should be noted that if we achieve widespread and affordable hydrogen availability, there will be competition with other sectors for it and this could require governments to enact policy incentives to prioritize the aviation sector. In addition, hydrogen use in aviation may be directed to the creation of power-to-liquid SAF, considering that using SAF doesn't require a change to aircraft design.

6.4 ACAS BY AIRCRAFT CLASS

In the previous section, general trends and possible ACA concepts are introduced, and discussed generally including mission applicability, associated challenges and potential impacts and timing. This section summarizes the earliest possible EIS years, energy intensity benefits relative to same year ATWs for each vehicle category in scenarios T2 and T3 and notes any mission limitation assumptions such as range. As such, the benefits provided by a given ACA concept relative to its reference aircraft were adjusted to the relevant year ATW.

The rationale for the earliest EIS years in each scenario was based on reports and evidence of past, present or planned ACA-relevant technology demonstrations or other research activity. More information on announced demonstrators is provided in this section. As expected, there are differences between the timeframes announced by various companies and research organizations for similar ACA concepts for a variety of reasons, but the potential EIS years reported in this section represent the EIS years that ACES members agreed on as representative of various estimates from the most credible studies for the purposes of the LTAG study.

Using authoritative reports and research activities to isolate the configuration and/or propulsion system impacts, ACES estimated the lower, medium and higher progress levels of impacts for ACAs with respect to ATWs for each technology scenario and for each vehicle category. Because ACES avoided selecting best, or winning concepts, the ACA impacts stated in this report do not come from a particular ACA concept and are representative of a range of ACA concepts considered under each technology scenario.

Regarding the potential mission limitations for some ACAs with non-drop-in fuels such as electricity and hydrogen, ACES had to consider ACAs with mission parameters vastly different from the relevant TRA and equivalent year ATW. In such situations, ACES prioritized keeping the payload and field length the same as ATW in order to not eliminate any airports under use. Knowing that most aircraft today are heavily used well below design ranges, ACES concluded that some range capability could be given up where use of non-drop-in fuel could be traded for some positive characteristic on lifecycle carbon emissions; the shorter range was often coupled with a slightly slower cruise speed as well. To estimate the energy intensity of a range-reduced ACA, estimates were required of equivalent year ATWs at the same mission parameters. To access a practical reduced range for such vehicles, ACES investigated the 2018 and 2050 fleet forecasts for fuel burn and operations to estimate an acceptable, reasonable reduction. To visualize where the majority of fuel burn and operations happen, heatmaps were plotted. Figure 6-14 and Figure 6-15 are included here as examples of the heatmaps. ACES identified the ranges with approximately 90% coverage of fuel burn and operations for each vehicle class. Then, ACES checked these ranges against the authoritative reports to finalize the range values for both ACA-T2 and ACA-T3 bins.

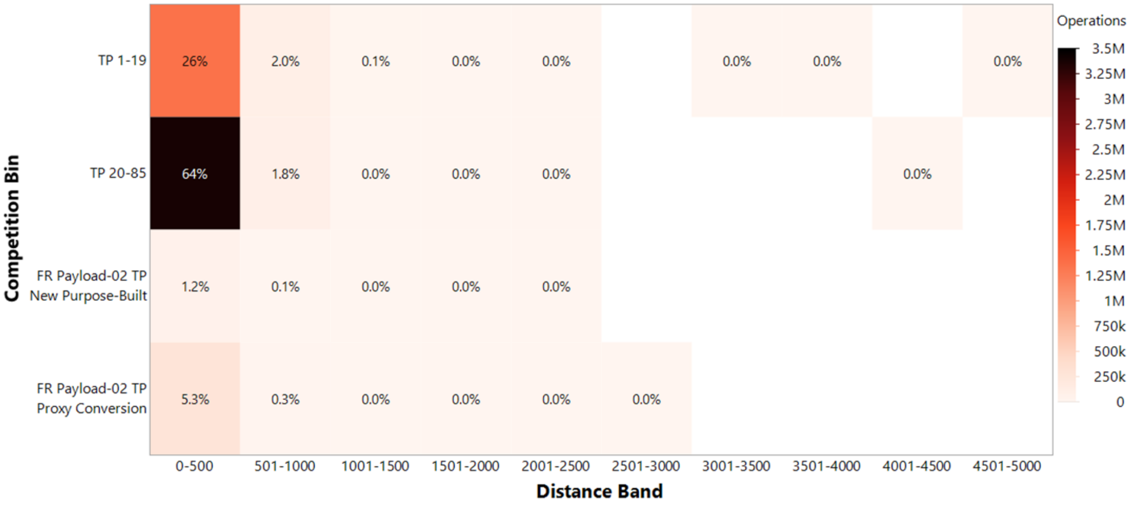

Figure 6-14. Competition Bin vs. Distance Band for Turboprop Operations (2018)

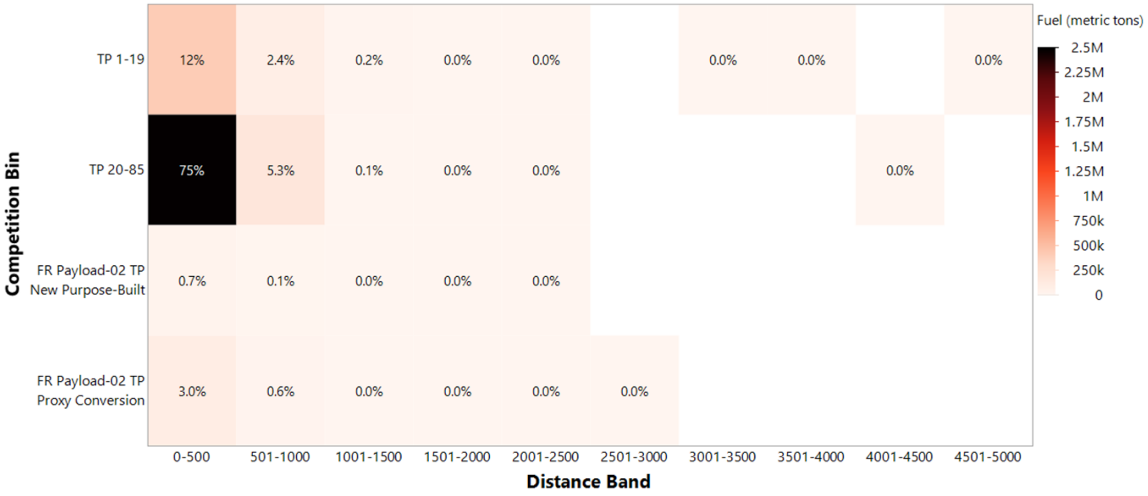

Figure 6-15. Competition Bin vs. Distance Band for Turboprop Fuel Burn (2018)

6.4.1 Turboprop ACAs

For the purposes of this study, ACES is projecting 2035 as the entry into service of T2 and T3 turboprop concepts. Some of the company announcements supporting this decision are provided here. De Havilland Canada announced that a collaboration with Pratt & Whitney Canada was formed to develop a hybrid-electric demonstrator using Dash 8-100 [52]. The ground testing is targeted to take place in 2022, and the flight testing in 2024. NASA has recently announced that two U.S. companies have been selected to support its Electrified Powertrain Flight Demonstrations (EPFD) to mature the propulsion technologies through ground and flight demonstrators. MagniX has received the award to demonstrate technology for short-range and regional air travel over the next five years.

Regarding hydrogen-powered aircraft, Airbus expressed their ambition to develop the world's first zero-emission commercial aircraft by 2035 and introduced the ZEROe concepts, one of which is a turboprop. Universal Hydrogen, on the other hand, plans to retrofit ATR 72 and Dash 8 class aircraft with hydrogen fuel-cell propulsion systems and solve the supply chain issue of hydrogen with their modular capsule technology [53]. Universal Hydrogen projects mid-2020s for the concept to be certified and enter into service. ZeroAvia has raised funding to start the development process for a 1.6-megawatt hydrogen fuel-cell powertrain for ATR42/72 and De Havilland Canada Dash 8 class turboprops. The powertrain's EIS is planned as 2026 [54]. The majority of the demonstrations are necessary precursors to development and certification of product aircraft, which often translates into a time lag to EIS. Unknowns on certification and in some cases sufficient energy infrastructure were also estimated to contribute to a time lag to EIS.

After a comprehensive scouting on company announcements, ACES concluded that smaller ACAs (below 50 passengers, approximately) could possibly enter service before 2035, some even by 2030;

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52 De Havilland Aircraft of Canada Limited, "De Havilland Canada Working with Pratt & Whitney Canada to Support the Development of Sustainable Hybrid-Electric Aircraft Propulsion Technology,", retrieved September 29, 2021 https://dehavilland.com/en/news/posts/de-havilland-canada-working-with-pratt-whitney-canada-to-support-the-development-of-sustainable-hybrid-electric-aircraft-propulsion-technology.

53 Aviation Week, "Tech Talk on How Universal Hydrogen Plans to Disrupt Aviation," retrieved September 29, 2021 https://aviationweek.com/aerospace/podcast-tech-talk-how-universal-hydrogen-plans-disrupt-aviation

54 Aviation Week, "Hydrogen Fuel Cells Advance as a Way to Decarbonize Regional Aviation," retrieved October 1, 2021. https://aviationweek.com/aerospace/aircraft-propulsion/hydrogen-fue.

however, the more significant impact on TP category from larger variants would likely be in 2035 and onwards for both T2 and T3 ACAs. Once the EIS assumptions were finalized, ACES identified the concepts that would be considered as T2 and T3 concepts. By definition, T2 concepts do not entail any dramatic infrastructure changes. Therefore, ACA-T2 bin for turboprop contains parallel hybrid-electric aircraft with time-limited in-flight charging and/or minor ground charging using existing electrical infrastructures around airports, while battery or hydrogen fuel cell hybrids are considered in ACA-T3 bin. Both the EIS assumptions and the turboprop ACA concepts that are binned under T2 and T3 scenarios are depicted in Figure 6-16.

The turboprop TRA's – De Havilland Canada Dash 8-400 – design range is 1,100nmi. The reduced range for T2 and T3 aircraft is estimated as 500nmi by using the heatmaps generated for turboprop category. Table 6-1 provides the ACES range of estimated energy efficiency benefits of the aircraft concepts in ACA-T2 and ACA-T3 bins, in terms of MJ/ATK, for 2035 and 2050 for all three-point estimates. The numbers represent the relative change in energy efficiency with respect to the ATWs of the same year. A positive value means that the energy intensity of ACA group is larger than that of ATW whereas a negative value indicates that ACAs are performing better than ATWs, keeping in mind that a higher energy intensity may not be considered a drawback from some perspective if it allows a significant carbon emissions reduction through the use of cleaner energy. ACES put forward these estimates after performing a thorough literature review on each concept while bearing in mind the technology bins and all concepts included in them.

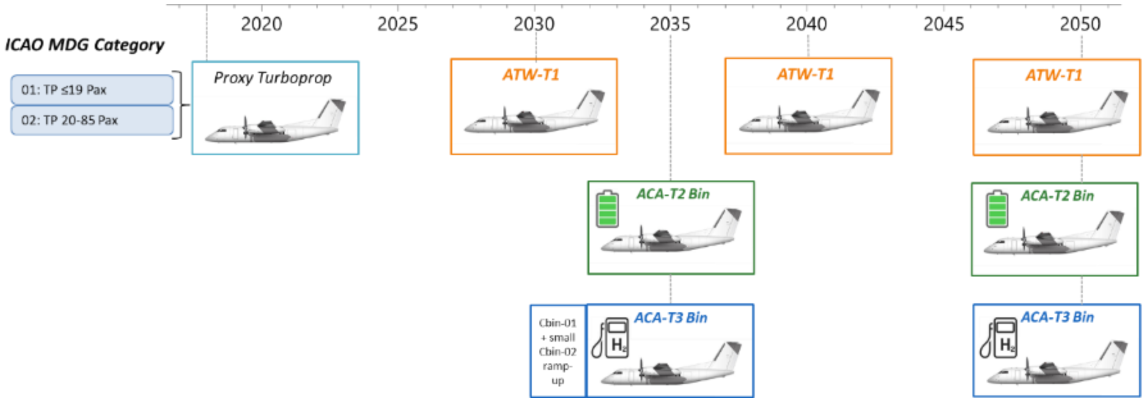

Figure 6-16. Turboprop ACA Identification of Earliest EIS

Table 6-1. Turboprop Energy Efficiency Benefits Relative to the Corresponding Year's ATW

Technology Scenario	Point Estimates	2035 Δ(MJ/ATK)	2050 Δ(MJ/ATK)
T2	Lower Progress	-5%	-5%
	Medium Progress	-10%	-10%
	Higher Progress	-15%	-20%
T3	Lower Progress	+10%	+10%
	Medium Progress	0%	0%
	Higher Progress	-10%	-10%

6.4.2 Business Jet ACAs

ACES members struggled to propose ACAs for business jets and to establish their energy efficiency benefits because there were very few publicly available authoritative studies and reports encompassing this vehicle category. Scaling was not considered to be a plausible approach because smaller aircraft sizes could not incorporate the advanced technologies developed for larger aircraft directly. For example, the engines of business jets use centrifugal compressors, and the design process has different trends for weight, fuel consumption and nacelle drag on fuselage-mounted engines. Since business jets have a smaller market, the economic opportunities for advanced technology insertion are also reduced. In addition to these economic and technological differences, the business jets are operated differently than other vehicle classes. Customers use all airports from the large hubs and very often the many smaller and remote airports that have shorter field lengths and that may be less likely to have the necessary infrastructures for ground charging or non-drop-in fuel options (such as hydrogen supply).

Because of these reasons, it was challenging for ACES members to identify the vehicle concepts that fall under the T2 and T3 scenarios. The Ascent business jet, designed by DZYNE Technologies (introduced in section 6.3.1.1), is one advanced configuration that could be considered in ACA-T2 bin. There are also electric concepts that are being studied by Ampaire, Inc. and Eviation. The Ampaire Tailwind is a clean-sheet design with hybrid-electric powertrain [55]. Eviation's Alice is a more conventional design with a T-tail and two tractor propellers on the aft of the fuselage. The company plans to perform the flight testing in 2021 and targets entry into service in 2024 [56]. All of these designs are included in ACA-T2 bin without any range restrictions on operations. From the LTAG member discussions, use of a future flex-fuel system capable of hydrogen use is chosen as a T3 concept. This concept would be able to operate on Jet-A, SAFs and hydrogen. Because of volume constraints, when flying with hydrogen, the range would be limited. This effect on operations is captured by assuming that the ranges over 1,000nmi would be flown with Jet-A or SAF, not hydrogen. The EIS of the T2 ACAs is estimated as 2035 by ACES. ACES agreed to have a five-year lag for flex fuel concept because it is at an earlier stage in its development. The ACA concepts and their projected EIS dates are depicted in Figure 6-17.

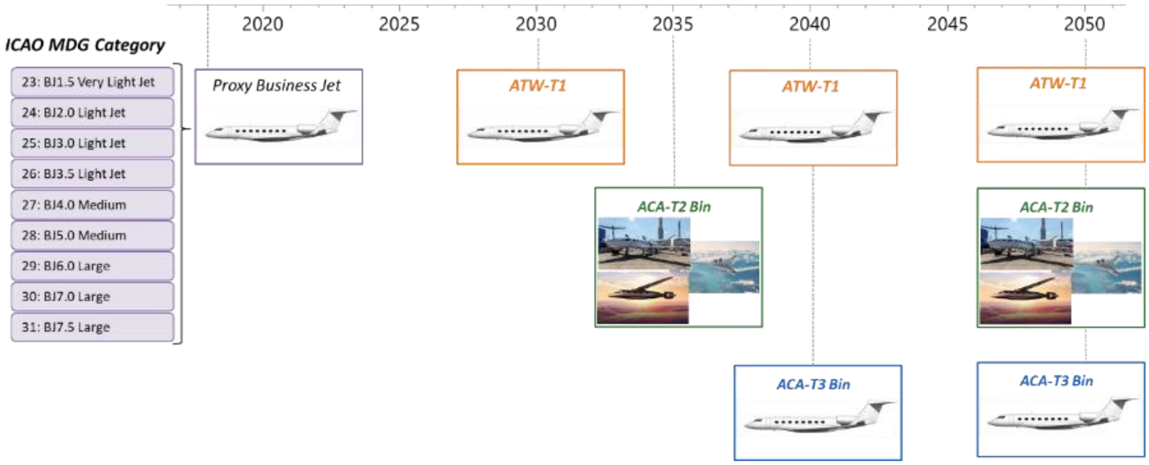

Figure 6-17. Business Jet ACA Identification of Earliest EIS

ACES needed to modify their approach to quantify the improvements in energy efficiency due to the lack of published or otherwise public information in this category. The business jet subgroup proposed applying half of the fuel burn improvement projected for regional jet ACAs because the regional jet is the closest in size to the larger business jets, and it is reasonable to assume that some fraction of the regional jet improvement could be applied to business jet class. All ACES members agreed on this approach, and the numbers used in this study are listed in Table 6-2.

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55 Amoaire, "Meet the Tailwind™," retrieved October 4, 2021
https://www.ampaire.com/vehicles/tailwind%E2%84%A2-aircraft

56 Aviation Week, "Eviation Redesigns Alice All-Electric Regional Aircraft," retrieved October 4, 2021
https://aviationweek.com/aerospace/aircraft-propulsion/eviation-redesigns-alice-all-electric-regional-aircraft

Table 6-2. Business Jet Energy Efficiency Benefits Relative to the Corresponding Year's ATW

Technology Scenario	Point Estimates	2035 Δ(MJ/ATK)	2040 Δ(MJ/ATK)	2050 Δ(MJ/ATK)
T2	Lower Progress	-2.5%	-	-2.5%
	Medium Progress	-5%	-	-5%
	Higher Progress	-7.5%	-	-10%
T3	Lower Progress	-	+15%	+15%
	Medium Progress	-	+5%	+5%
	Higher Progress	-	0%	0%

6.4.3 Regional Jet ACAs

ACES could find relatively little evidence of ACA-relevant demonstrations specific to regional jets as the focus is significantly more on the narrow body class with regard to advanced airframe, propulsion and energy concepts. However, due to the significant similarities and increasing overlap in mission, ACES leveraged the information gathered for narrow body when identifying the ACAs for T2 and T3 scenarios and the projected entry into service dates as well as the relative energy efficiency benefits as shown in Figure 6-18 and Table 6-3, respectively. The regional jet TRA's – Embraer E190-E2 – design range is 3,350nmi. The reduced range for T3 aircraft is estimated at 1,000nmi by using the heatmaps generated for RJ category.

Figure 6-18. Regional Jet ACA Identification of Earliest EIS

Table 6-3. Regional Jet Energy Efficiency Benefits Relative to the Corresponding Year's ATW

Technology Scenario	Point Estimates	2035 Δ(MJ/ATK)	2050 Δ(MJ/ATK)
T2	Lower Progress	-5%	-5%
	Medium Progress	-10%	-10%
	Higher Progress	-15%	-20%
T3	Lower Progress	+20%	+20%
	Medium Progress	+15%	+15%
	Higher Progress	-5%	-5%

6.4.4 Narrow Body ACAs

Aviation industry and research organizations have a high degree of focus in the narrow body category due to its high utilization. As such considerable research and development focus on relevant revolutionary concepts and enabling technologies in the category, noting also that many technologies could potentially be applied to other vehicle classes as well. The ACAs the ACES group decided to group under T2 scenario include advanced aircraft configurations with advanced wings such as truss-braced wings and boxed wings, hybrid/blended wing-bodies, unducted fans, and mild hybrid electric propulsion as these ACAs do not require major infrastructure changes.

The NASA-led US government Sustainable Flight National Partnership (SFNP) [57] has recently announced relevant major demonstrations inclusive of ACA-relevant airframe/configuration technology and the EFPD including NB relevant electrified powertrain flight demonstration. SFNP aims to make technology ready for industry design consideration in time for early 2030s EIS. According to the RISE program announcement, inclusive of UDF and hybrid electric technology, CFM and GE Aviation plan to start testing in the mid-2020s and then move to the flight testing. They envision that their engines could enter service by the early 2030s. Exploring the development of disruptive technologies such as hydrogen and hybrid-electric is also in their agenda.

While mild hybrid electric technology falls under T2, the hydrogen-based concepts fall under T3 scenarios due to the estimated larger reliance on significant infrastructure change. For this vehicle class, the concepts that are collected under T3 include electric propulsion and hydrogen-powered aircraft with either advanced conventional or alternative airframe – most likely modified conventional airframes initially -, ACES agreed that having substantial propulsion system change and configuration change at the same time is highly unlikely. Similar to T2, the projected EIS for T3 ACAs is 2035. Airbus' ZEROe program includes consideration of a reduced range (2000nmi+), hydrogen-powered NB by 2035 and is indicative of industry's real interest in hydrogen. Figure 6-19 demonstrates the ACA concepts and their EIS years for the narrow body category.

Table 6-4 shows the energy efficiency benefit percentage estimates for lower, medium and higher progress levels. The values are representative of results from a range of authoritative reports, research studies and company announcements considering all concepts under each technology scenario.

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[57] NASA, "NASA Aims for Climate-Friendly Aviation", retrieved October 7, 2021 https://www.nasa.gov/aeroresearch/nasa-aims-for-climate-friendly-aviation

Figure 6-19. Narrow Body ACA Identification of Earliest EIS

Table 6-4. Narrow Body Energy Efficiency Benefits Relative to the Corresponding Year's ATW

Technology Scenario	Point Estimates	2035 Δ(MJ/ATK)	2050 Δ(MJ/ATK)
T2	Lower Progress	-5%	-5%
	Medium Progress	-10%	-10%
	Higher Progress	-15%	-20%
T3	Lower Progress	+20%	+20%
	Medium Progress	+15%	+15%
	Higher Progress	-5%	-5%

6.4.5 Wide Body ACAs

The ACAs considered for wide body class are similar to those of narrow body because many NB concepts could be applied to wide body in some form – due to higher cruise speeds, the UDF is not considered for the WB. The only change from narrow body is the EIS year of T3 concepts. ACES members believe that the narrow body or regional jet would serve as a pathfinder for the ACA-T3 concepts, and it would take around 15 years to apply them to wide body aircraft. As shown in Figure 6-20, ACES decided to have wide body T3 concepts enter service in 2050. Given the time and the studies that indicate hydrogen-powered aircraft efficiency likely increases with range, it was estimated that by 2050 there will be no reason to have a range constraint and avoid the resulting requirement for a second conventional wide body to fly the longer ranges.

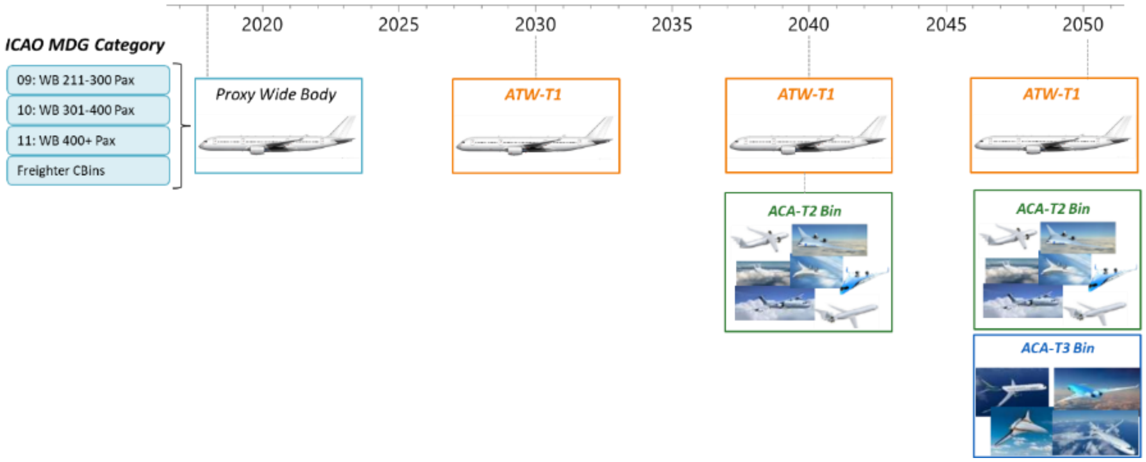

Figure 6-20. Wide Body ACA Identification of Earliest EIS

The energy efficiency benefits for T2 are the same as those of narrow body. ACES is of the opinion that T3 ACAs that are entering into service in 2050 have the potential to perform better than narrow body ACAs as shown in Table 6-5 due to the theoretical efficiency improvement with size/range for hydrogen aircraft.

Table 6-5. Wide Body Energy Efficiency Benefits Relative to the Corresponding Year's ATW

Technology Scenario	Point Estimates	2035 Δ(MJ/ATK)	2050 Δ(MJ/ATK)
T2	Lower Progress	-5%	-5%
	Medium Progress	-10%	-10%
	Higher Progress	-15%	-20%
T3	Lower Progress	-	+40%
	Medium Progress	-	0%
	Higher Progress	-	-10%

6.5 NEW AIRCRAFT FOR EMERGING MISSIONS

While subsonic fixed wing aircraft represented the LTAG TRAs and their future versions represent the vast of majority of commercial air transportation, there are several emerging markets. Two primary emerging mission examples are Urban Air Mobility (UAM) and supersonics. There are many companies and research institutes working on such UAM concepts, from small, unmanned aircraft systems (UAS) to provide package delivery for example, and short-range vertical take-off/landing vehicles that could serve many purposes including air taxi services. Though the potential markets are large, the missions envisioned are essentially domestic and outside the scope of LTAG which focuses on international travel. The UAM vehicle missions are very much like that of helicopters which are not considered as well. For these UAM vehicles to be successful, they will need to address sustainability from day 1 to succeed and compete against other local modes of transport on the ground. Electrification is a key research focus and technology element in this class, so access to clean grids is critical, much as it is for ground vehicles. It is the same with airships, another facet of aviation that is rising again with several projects across the world, that would mostly bring

CO_2 reduction benefits out of the aviation sector, through domestic operations mainly in the field of logistics, replacing other means of heavy goods transportation.

Supersonic missions are a different matter. They differentiate themselves through significantly higher speed relative to subsonic vehicles over long ranges, for example trans-Atlantic routes, and are inclusive of but not limited to international travel. The commercial supersonic market is in the process of reemerging after a dormant period since the Concorde retired with fleets envisioned in the hundreds, not thousands. Several companies [58, 59] are dedicated to bringing back supersonic travel and make it economically viable thanks to new materials, advanced engines and innovations in aerodynamics. The focus is on long range BJ travel and premium class airliners in the 40-80 passenger class markets which are currently served by subsonic travel options.

Supersonic flights require more fuel/energy than equivalent (payload/range) subsonic flights due to the higher speed. For aircraft currently being studied cruise speed ranges from Mach 1.4 to 2.2. As the supersonic cruise Mach number increases, so does the difference in energy use, leading to a focus below Mach 2. Similarly, fuel use increases with improving LTO noise margins relative to regulations as well. In addition to the supersonic cruise Mach number sensitivity, the design choices around cabin/passenger density, supersonic/subsonic cruise segments/capability, and sonic boom levels significantly impact energy intensity. The trade space of future supersonic aircraft design choices and mission parameters is large and estimates of energy intensity vary with these choices and assumed technology levels and time horizons. It is reasonable to assume supersonic aircraft may be several times more energy intensive that subsonic aircraft. Increased energy intensity of 3-4 times is likely but not a definitive upper or lower boundary as new designs continue to be refined. The developers are committed to provide faster transportation in a sustainable manner and counter the increased CO_2 using SAF. Boom, for example, has announced that their Overture aircraft will be capable of operating on 100% SAF [60]. NASA's X59 low-boom flight demonstrator [61] will soon demonstrate design technology that could enable supersonic flight overland. Data from community overflights will be collected by NASA with collaboration from international partners and provided to ICAO and other organizations with the purpose of eliminating rules banning supersonic overland flight. The impact of increased emissions, particularly at higher altitudes with longer-lasting effects, remains a concern from supersonic flights which cruise inherently higher with increased design Mach. Due to the relatively small market size and plans to use 100% SAF from day 1, LTAG did not model this class of vehicle and mission within the study.

6.6 ACA OBSERVATIONS

The ACA assessment methodology was more qualitative in nature and are not based on MDAO design efforts as assembled for the ATWs. The ACA methodology yielded timelines about the earliest potential entry into service (EIS) as well as tables recording energy efficiency for all five vehicle classes based on a qualitative review of reputable documents and studies of numerous concepts. Observations were drawn and representative ACAs were identified for each vehicle class and timeframe.

From the qualitative perspective, the LTAG Tech/ACES Tahg in partnership with other Tahgs studied a wide range of ACAs across the LTAG Tech aircraft categories. ACES relied on existing publicly available

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[58] Boom: https://boomsupersonic.com/

[59] Spike Aerospace: https://www.spikeaerospace.com/

[60] Boom, "How Will Supersonic Travel Be Sustainable and Ensure a Quieter Ride? Boom and Japan Airlines Highlight 5 Initiatives," retrieved October 7, 2021. https://boomsupersonic.com/flyby/post/how-will-supersonic-travel-be-sustainable-and-ensure-a-quieter-ride-boom-and-japan-airlines-highlight-5-initiatives

[61] NASA, "Low-Boom Flight Demonstration Overview," retrieved October 8, 2021. https://www.nasa.gov/X59

material rather than the modeling approach taken with the ATWs. ACES developed consensus estimates of the potential timing and benefits of the ACAs grouped by LTAG aircraft categories of TP, RJ, NB, WB, and BJ, without predicting any winning concepts out of the many alternatives. **ACES led the LTAG Tech assessment of ACAs. Existing published material was used to develop consensus on potential timing and estimated benefits for each aircraft category. Care was taken to not suggest specific winning aircraft concepts.**

ACAs are defined by step-changes to technology and/or vehicle system or subsystem architecture enabling performance/capability beyond the same-year ATWs. Development and maturation of technologies and configuration technologies need to progress to sufficient Technology and Integration Readiness levels to be considered by OEM's for detailed design and manufacturing assessment. Such changes will remain difficult to achieve and the technical ability to do something remains a necessary but not sufficient condition to enable new commercially viable product. The decision to take the leap will be made by informed business leaders making business decisions. Government sponsored R&D can reduce the technical risks, while government policy can influence the trade space for change. **Change is always hard. Step-change is harder. Technical capability and maturity are necessary but not sufficient conditions to implement a configuration step change.**

Several major global drivers are active now that will affect future technology and configuration developments. Climate change and the recovery from the global pandemic are worldwide drivers beyond the aviation sector alone. Aviation has always been a leader driving innovation on the path to a more sustainable future that considers the needs of society, business, and the environment. Today's combination of factors sets the stage for revolutionary change. **Major global drivers beyond the aviation sector are active now. The combination of factors sets the stage for an ACA-driven revolution in aviation to help provide further emission reductions.**

There are many ACA-relevant technology development and demonstration activities ongoing and recently announced. Most focus on the smaller vehicle classes from commuters to small BJ and TP missions and predominantly aim to modify existing airframes with scenario T2-like electrification or T3-like hydrogen use. These missions will provide opportunities to learn about technology, certification, and operation of these ACA systems, but contribute relatively little by percentage to aviation's carbon reduction. Fortunately, there is already activity directed at larger TP markets. Though fewer at the moment, there is significant activity focused on ACA-relevant airframe and propulsion opportunities for next generation NBs with relevance to RJ, and ultimately, to WB classes. **Significant ACA-relevant R&D is underway or planned for the next decade, including flight demonstrations. Most near-term application is envisioned first for smaller aircraft, e.g. smaller TP aircraft. Smaller aircraft can provide learning opportunities for technologies that scale to larger aircraft (RJ and NB). Larger aircraft will have more impact on carbon reduction but lag in time.**

ACA-relevant alternative airframes are possible by 2035 and may yield an additional 10-15% energy intensity reduction beyond same-year ATWs. Most effort is focused on larger aircraft. Hybrid wing-bodies and truss-bracing concepts appear furthest along the readiness curve at this point, but not far enough yet for design of next generation aircraft. Airframe-centric ACAs will utilize many of the same underlying technologies as ATWs and may open the design space for alternative propulsion and propulsion-aircraft integration. Much remains to make these concepts technically ready for true consideration in the industry design trade space, not the least of which is a large-scale, integrated demonstration. Additionally, concept-specific non-technical attainability challenges such as new methods of compliance for certification and any unique operational integration challenges will need to be fully addressed. **ACA-relevant airframes are assumed in current study to be possible by 2035. Large-scale, integrated flight demonstration is required. Possible energy intensity reduction due to configuration step change between 5-15% compared to ATWs is assumed.**

ACA-relevant alternative propulsion systems are possible by 2035 and may yield 10-15% energy intensity reduction beyond same-year ATWs. Effort is spread across the full LTAG aircraft category range with more demonstrations ongoing for the smaller aircraft where electrification and the use of hydrogen fuel are two primary thrusts. For larger aircraft, the unducted fan concept has been studied extensively and will require a full-scale integrated flight demonstration to be made technically ready. Propulsion-centric ACAs will utilize many of the same underlying ATW engine technologies. Concept-specific non-technical attainability challenges will need to be overcome, not the least of which is the integratability with and availability of an alternative energy infrastructure in some cases. **ACA-relevant propulsion with or without alternative energy is possible by 2035. Alternative energy solutions are highly dependent of availability of energy infrastructure. Large-scale, integrated flight demonstration is required. Energy intensity reduction between 5-15% compared to ATWs is assumed.**

Electrified Aircraft Propulsion is coming and will take a variety of forms. Hybrid architectures will likely have the most impact on carbon reduction first with small but favorable benefits initially while the weight of electric components improves. Additional benefits of electric propulsion are low noise, lower maintenance and, for full-electric propulsion, zero exhaust emissions. Carbon benefits are highly dependent on the local electric grid or the source of hydrogen in fuel cells, which are likely to improve over time following the worldwide transition to more renewable energy. Additionally, the smaller aircraft that will rely more on batteries or fuel cells or will be range constrained, while the large aircraft employing a milder hybrid approach will not be mission constrained, but their emission reduction will be limited. **Electrified aircraft propulsion is coming. Initial benefits will be small but significant and instigate change. Hybrid systems are likely initially to balance weight and range challenges. The carbon reduction from electrification is highly dependent on local grids around the world.**

Hydrogen-fueled aircraft R&D is active and such aircraft may be achievable technically, and likely more attainable technically relative to non-technical challenges and commercial viability. The main challenges reside outside of the aviation industry, namely with the cryogenic hydrogen production infrastructure readiness and the availability of green electricity to produce the hydrogen. Hydrogen has energy density and mass benefits, but given the volume requirements, hydrogen aircraft will likely either lose payload or range capacity, or both, compared to similarly sized conventional aircraft. The larger aircraft may have more capacity to adapt to the volume requirement with minimal penalty in the far term. The main advantage of hydrogen is that it is a fuel containing no carbon, and if it is produced through electrolysis using renewable electricity, its carbon footprint is close to zero. The use of hydrogen whether for fuel cells or in combustion will require substantial investment in infrastructure and the life cycle carbon benefits highly dependent on the method of its production. **Hydrogen-fueled aircraft may be achievable technically and reduce in-flight carbon emissions to zero. The non-technical attainability challenges and commercial viability are likely greater challenges to overcome. Aircraft design and mission capability trades will be impacted due to the properties of hydrogen. Energy use may increase to yield a decrease in carbon emissions in flight. The life cycle carbon reduction benefits will be highly dependent on the production method for the hydrogen.**

Significant change including ACAs is possible in the timeframe between now and 2050, but given the long timelines of technology maturation, product development and certification, and time for impactful fleet penetration, we have no time to waste. Any change to an alternative architecture will require large-scale, high-cost integrated demonstration before change may occur. Timelines for the highest impact vehicles relative to carbon emissions project EIS dates approaching 2035. For the T3 scenario, the infrastructure barriers will have to be on at least an equal timeline to the aircraft. Timelines for the highest impact vehicles relative to carbon emissions project EIS dates approaching 2035. And for T3, business models may have to change if key technologies that enable substantial carbon reduction require substantially reduced ranges. **Change is possible by 2035, but there is no time to waste. ACAs will require large scale demonstrations. In the case of non-drop-in energy, substantial change to the energy infrastructure available to aviation in required. Business models may have to change also adapting to low carbon aircraft range capabilities.**

APPENDIX M3.7. TECHNOLOGY SUB GROUP INPUT TO MDG, FESG, AND LTAG

7.1 INTRODUCTION

To assess the environmental improvements due to aircraft technologies, the results discussed in APPENDIX M3.5 and APPENDIX M3.6 must be propagated to the fleet-level. To enable this step, interfaces between the Tech SG, FESG, MDG, and the Cost Estimation ad hoc group are needed. This chapter outlines the outputs out of the ATW vehicle modelling and ACA impact forecasts that were formatted in ways to be useful for MDG and FESG modelling downstream. The follow-on calculations take the market share and energy intensity reduction and forecast costs and fuel demand of international aviation. Additionally, results from both ATW and ACA analyses are integrated into a single timeline and improvement charts in this chapter.

7.2 DATA NEEDED FOR MDG, FESG, AND SDSG

The key inputs needed by the fleet-level fuel demand modeling are predicted trends in energy use per available tonne kilometers (MJ/ATK), i.e. energy intensity measuring the energy needed for a unit transportation activity, and mix of ATW-T1 vs. ACA-T2 vs. ACA-T3 entering the fleet in a given year, i.e. market share. Energy intensity trend calculations are based on results in APPENDIX M3.5 and APPENDIX M3.6, while market share trends were determined by investigating the historical trends of new aircraft introductions to the fleet and subject matter expert input. Both energy intensity and market share predictions are made for each vehicle class and technology level (T1–3) separately; however, only energy intensity predictions were provided with a three-point estimate of lower/medium/higher progress.

Energy intensity (EI) for ATW-T1s were derived from the modelling results provided in 4 distinct future years: 2018 (TRA), 2030, 2040, and 2050. The models provide a value for kilogram of fuel burn per ATK with the assumption of burning Jet-A fuel. Using the energy density of Jet-A fuel of 42.8 MJ/kg, energy intensities of the 2018 TRA as well as 2030/2040/2050 ATW-T1 are calculated for each class of vehicle as given in Equations 5-1 and 7-1. Energy Intensity is given in non-standard units of MJ/ATK as agreed upon by the parties performing the study. Once ATW-T1 energy intensities are calculated, ACA-T2 and ACA-T3 improvement delta factors can be applied, using Equation 7-2. Both energy intensity and ACA delta improvement predictions are functions of future years.

$$EI\left[\frac{MJ}{ATK}\right] = \frac{Fuel\,Burn[kg]}{Activity[ATK]}\frac{E[MJ]}{Fuel[kg]} \tag{7-1}$$

$$EI_{ACA}(Y) = \left(1 + \Delta_{ACA}(Y)\right) \times EI_{ATW}(Y) \tag{7-2}$$

Energy intensities for ATW-T1s are calculated only on select waypoint years, and a continuous function is needed to calculate their values in the between years. Traditionally, a yearly factor is used to turn waypoints into a continuous function. This factor is named *per annum improvement*, α. The line between the two waypoint years is therefore slightly curved to form a smooth function. The smoothness is lost at the waypoint years although the function is still continuous. To calculate the energy intensity for between years, Equation 7-3 is used where the energy intensity at the earlier waypoint year is multiplied by per annum improvement raised to the power of number of years between waypoints to calculate the energy intensity at the next waypoint year. Finally, to interface well with MDG model input, raw energy intensity values will be converted into energy improvement factors (ε) based on the 2018 TRA as given in Equation 7-4. Using this factor, MDG will scale down energy needs of future more energy efficient aircraft. Aircraft that are more energy efficient than the TRA will have $\varepsilon \leq 1$. Energy efficiency factor has an absolute scale, i.e.

an energy efficiency factor of 0 means the design does not need energy to move payload over a distance, which is an absolute physical limit, meaning that the number cannot be less than 0.

$$EI(Y_{w+1}) = \alpha^{Y_{w+1} - Y_w} EI(Y_w) \tag{7-3}$$

$$\varepsilon(Y) = \frac{EI(Y)}{EI_{ATW}(2018)} = \frac{EI(Y)}{EI_{TRA}} \tag{7-4}$$

Initially, Tech SG output only included the ATW-T1 energy efficiency factors in the waypoint years, ATW-T1 per annum improvements for each interval, and the ACA delta improvements. The assumption for the format was that the per annum improvements would be constant for ATWs and ACAs. However, due to a later decision to model ACA improvements as a smooth curve that is a function of years, ACA energy intensity factor calculations required additional per annum factors to be implemented. The most unambiguous output was determined to be a year-by-year timeline of ATW-T1, ACA-T2, and ACA-T3 energy efficiency factors and not report on multiple per annum values due to traditional technology improvements and conceptual improvements. The year-by-year factors were calculated by Tech SG for visualization purposes, independent of MDG needs.

The second part of the input to MDG was in the form of earliest entry into service years and a market share split between ATW-T1, ACA-T2, and ACA-T3 vehicles for each integrated scenario. In the integrated scenarios, ACA-T3 was made available only in the most aggressive IS3, ACA-T2 was made available on medium IS2 and aggressive IS3, and ATW-T1s were available regardless of the scenario. Table 7-1 shows the availability of vehicles for each integrated scenario and Table 7-2 shows the earliest entry into service for ACA-T2 and ACA-T3s for each vehicle class as rationalized in the prior chapter. The market share percentages for each vehicle class were established by the Cost Estimation ad hoc group based on prior production capabilities by class.

Table 7-1: Availability of Vehicles in Different Integrated Scenarios Regardless of Vehicle Class

	IS1	IS2	IS3
ATW-T1	✓	✓	✓
ACA-T2		✓	✓
ACA-T3			✓

Table 7-2: Earliest Entry into Service Years for Advanced Concept Aircraft

		Turboprop	Regional Jet	Narrow Body	Wide Body	Business Jet
IS1	ATW-T1	—	—	—	—	—
IS2	ATW-T1	—	—	—	—	—
	ACA-T2	2035	2035	2035	2040	2035
IS3	ATW-T1	—	—	—	—	—
	ACA-T2	2035	2035	2035	2040	2035
	ACA-T3	2035	2035	2035	2050	2040

The simplest case is Integrated Scenario 1 where the entire market for new aircraft and replacement is taken by ATW-T1 vehicles for each class of vehicles. For IS2 and IS3, based on historical production trends a market share is provided as an output. The market share split between the ATW and ACA vehicles are different for different classes of vehicles taking production capabilities into account. The trends are given in the subsections below. Introducing ACA-T2s in the IS2 scenario reduces the ATW-T1 market share resulting in an energy efficiency increase in the fleet. Similarly, introducing the ACA-T3 in IS3 reduces the market share of both ATW-T1s and ACA-T2s. The dynamics are complex for this case and fleet modeling results are needed to assess the carbon-saving benefits.

There are two important notes to keep in mind for the trends. First note is that the delivery market shares in future years is rounded to the nearest 5% by the FESG; therefore, the scenario must be taken as a possible scenario, not a precise prediction of the future. Second note is that the trends continue beyond 2050 through 2070 while the technologies of the vehicles stay fixed. The reason to continue the trends is to assess the technology benefits by 2050 as they need to be introduced to the fleet over time to have an impact. Otherwise, the effects of new vehicles and technologies introduced near 2050 would be impossible to assess.

In the following charts for each vehicle class, the orange aircraft represent the ATW-T1s, green aircraft represent the ACA-T2s, and blue aircraft represent the ACA-T3s. The bands around the medium progress line represent the uncertainty between the lower and higher progress scenarios. Medium progress line is not necessarily the average of the lower and higher progress as the uncertainty distributions is not assumed to be symmetric.

7.3 TURBOPROP INPUT FOR FLEET-WIDE MODELING

Turboprop energy intensity input for the MDG is summarized in Table 7-3 and Table 7-4 below. The energy intensity tables are only summary results, and the full results are given in Appendix G.1. In the turboprop class of vehicles, roughly a 21% reduction of energy use is predicted by 2050 with the advanced tube and wing concepts. For detailed reduction calculations please refer to Table 5-2.

Table 7-3: Turboprop ATW-T1 Energy Intensity at Each Waypoint Normalized to the TRA

Energy Intensity Relative to 2018 TRA			Turboprop			
			2018	2030	2040	2050–2070
T1	ATW-T1	Lower Progress	100.00%	93.77%	88.14%	85.43%
		Medium Progress		88.04%	82.17%	79.24%
		Higher Progress		84.07%	77.95%	74.87%

The earliest a turboprop ACA-T2s to enter into service was forecast to be in 2035 with a likely improvement over the contemporary ATW of 5 to 15%. The band of the advantage is expected to grow by 2050 with a 20% improvement achievable with higher progress. The higher progress ACA-T2 impact was modeled as a continuous improvement between 2035 and 2050 similar to the continuous improvements between decades of ATW efficiency. ACA-T3 variants with non-drop-in fuels may be 10% more or less efficient than an ATW. Please refer to Section 6.4.1 for detailed discussion how the improvements were predicted.

Table 7-4: Turboprop ACA Energy Intensity Deltas from The Respective ATW-T1 of the Same Year

ACA Energy Intensity Change Relative to Same Year's ATW			Turboprop			
			2018	2030	2035	2050–2070
T2	ACA-T2	Lower Progress	—	—	-5.00%	-5.00%
		Medium Progress	—	—	-10.00%	-10.00%
		Higher Progress	—	—	-15.00%	-20.00%
T3	ACA-T3	Lower Progress	—	—	10.00%	10.00%
		Medium Progress	—	—	=ATW	=ATW
		Higher Progress	—	—	-10.00%	-10.00%

The trend plots provided in Figure 7-1 and Figure 7-2 are alternative representations of the tabular data with including uncertain progress bands. Figure 7-1 combines the entry into service and technology impacts of new entries. Figure 7-2 visualizes the relative scale of the uncertainties in the future years compared to the median expected progress.

	MJ/ATK	Relative to TRA
2018 TRA	8.807	100.0%

	MJ/ATK	Relative to TRA
Lower Progress	8.258	93.8%
Medium Progress	7.753	88.0%
Higher Progress	7.404	84.1%

	MJ/ATK	Relative to TRA
Lower Progress	ATW – 5%	86.4%
Medium Progress	ATW – 10%	76.5%
Higher Progress	ATW – 15%	68.8%
Lower Progress	ATW + 10%	100.0%
Medium Progress	=ATW	85.1%
Higher Progress	ATW – 10%	72.9%

	MJ/ATK	Relative to TRA
Lower Progress	7.762	88.1%
Medium Progress	7.237	82.2%
Higher Progress	6.865	78.0%

	MJ/ATK	Relative to TRA
Lower Progress	7.524	85.4%
Medium Progress	6.978	79.2%
Higher Progress	6.594	74.9%
Lower Progress	ATW – 5%	81.2%
Medium Progress	ATW – 10%	71.3%
Higher Progress	ATW – 20%	59.9%
Lower Progress	ATW + 10%	94.0%
Medium Progress	=ATW	79.2%
Higher Progress	ATW – 10%	67.4%

Figure 7-1: Turboprop ATW Waypoints, ACA Entry Into Service and Energy Intensity Values

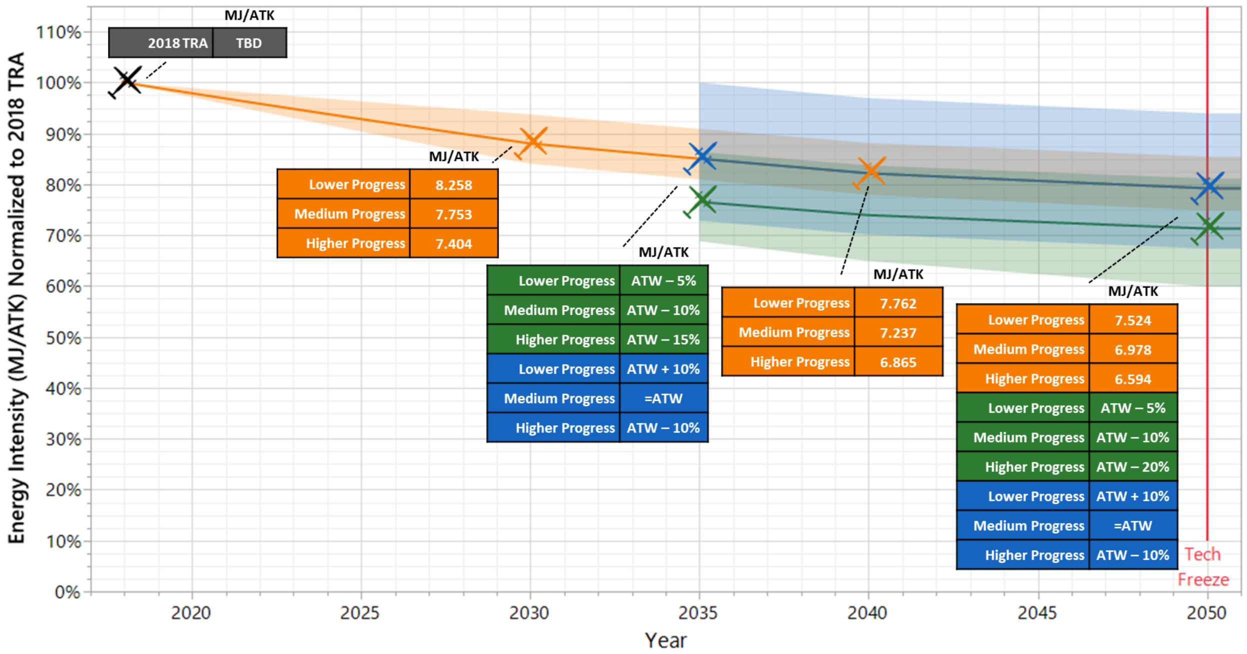


Figure 7-2: Turboprop Technology and Concept Energy Intensity Trend Normalized to the 2018 TRA

The market share table completes the input to MDG and is given in Table 7-5 and Figure 7-3. By 2050, it is forecast that the majority of the market share will switch to ACAs for both IS2 and IS3. Market share figures are rounded to the nearest 5% in the future years consistent with FESG process and assumptions.

Table 7-5: Turboprop Market Shares for New Entry and Replacements

Market Share for New Deliveries		Turboprop					
		2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	75%	40%	10%	0%
	ACA-T2			25%	60%	90%	100%
IS3	ATW-T1	100%	100%	60%	20%	10%	0%
	ACA-T2			20%	40%	45%	50%
	ACA-T3			20%	40%	45%	50%

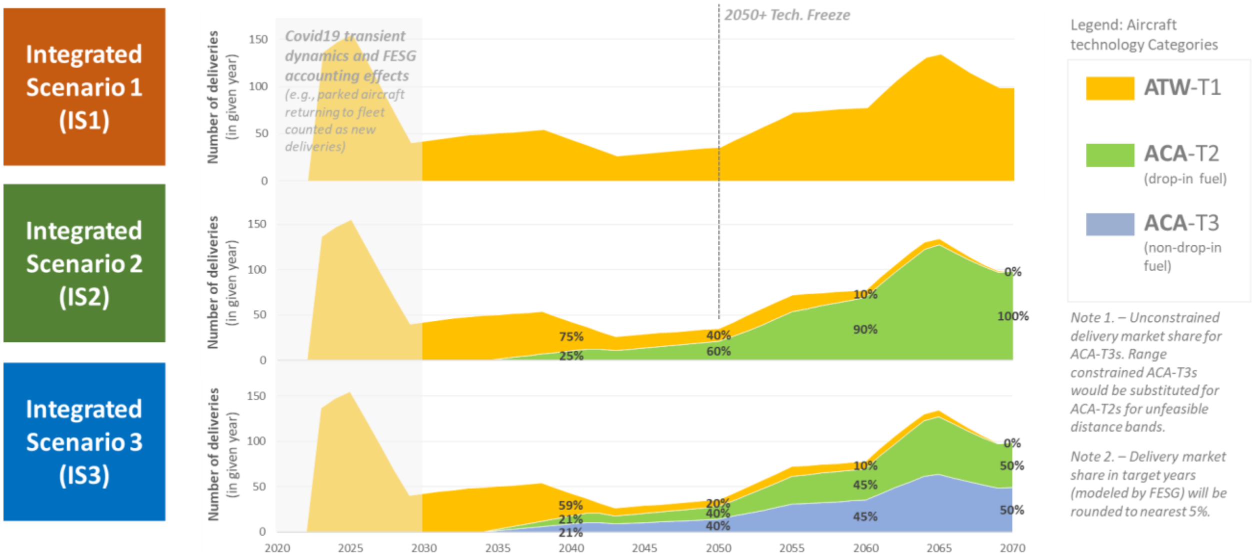


Figure 7-3: Market Share Timeline for Turboprop Class of Vehicles

7.4 BUSINESS JET INPUT FOR FLEET-WIDE MODELING

Business Jet energy intensity input for the MDG is summarized in Table 7-6 and Table 7-7 below. The energy intensity tables are only summary results, and the full results are given in Appendix G.2. In the business jet class of vehicles, a 20% reduction of energy use is predicted by 2050 with the advanced tube and wing concepts. For detailed reduction calculations please refer to Table 5-3.

Table 7-6: Business Jet ATW-T1 Energy Intensity at Each Waypoint Normalized to the TRA

Energy Intensity Relative to 2018 TRA			Business Jet			
			2018	2030	2040	2050–2070
T1	ATW-T1	Lower Progress	100.00%	95.26%	90.02%	85.18%
		Medium Progress		90.52%	84.79%	80.08%
		Higher Progress		87.34%	79.90%	74.96%

The earliest a business jet ACA-T2s to enter into service was forecast to be in 2035 with a likely improvement over the contemporary ATW of 2.5 to 7.5%. The band of the advantage is expected to grow by 2050 with a 10% improvement achievable with higher progress. The higher progress ACA-T2 impact was modeled as a continuous improvement between 2035 and 2050 similar to the continuous improvements between decades of ATW efficiency. ACA-T3s are not expected to enter into service before 2040. ACA-T3 variants with non-drop-in fuels may be 15% less efficient than a contemporary ATW. Please refer to Section 6.4.2 for detailed discussion how the improvements were predicted.

Table 7-7: Business Jet ACA Energy Intensity Deltas from The Respective ATW-T1 of the Same Year

ACA Energy Intensity Change Relative to Same Year's ATW			Business Jet				
			2018	2030	2035	2040	2050–2070
T2	ACA-T2	Lower Progress	—	—	-2.50%	…	-2.50%
		Medium Progress	—	—	-5.00%	…	-5.00%
		Higher Progress	—	—	-7.50%	…	-10.00%
T3	ACA-T3	Lower Progress	—	—	—	15.00%	15.00%
		Medium Progress	—	—	—	5.00%	5.00%
		Higher Progress	—	—	—	=ATW	=ATW

The trend plots provided in Figure 7-4 and Figure 7-5 are alternative representations of the tabular data with including uncertain progress bands. Figure 7-4 combines the entry into service and technology impacts of new entries. Figure 7-5 visualizes the relative scale of the uncertainties in the future years compared to the median expected progress.

	MJ/ATK	Relative to TRA
2018 TRA	27.141	100.0%

	MJ/ATK	Relative to TRA
Lower Progress	25.856	95.3%
Medium Progress	24.569	90.5%
Higher Progress	23.706	87.3%

	MJ/ATK	Relative to TRA
Lower Progress	ATW – 2.5%	90.3%
Medium Progress	ATW – 5%	83.2%
Higher Progress	ATW – 7.5%	77.3%

	MJ/ATK	Relative to TRA
Lower Progress	24.433	90.0%
Medium Progress	23.013	84.8%
Higher Progress	21.686	79.9%
Lower Progress	ATW + 15%	103.5%
Medium Progress	ATW + 5%	89.0%
Higher Progress	=ATW	79.9%

	MJ/ATK	Relative to TRA
Lower Progress	23.119	85.2%
Medium Progress	21.734	80.1%
Higher Progress	20.345	75.0%
Lower Progress	ATW – 2.5%	83.1%
Medium Progress	ATW – 5%	76.1%
Higher Progress	ATW – 10%	67.5%
Lower Progress	ATW + 15%	98.0%
Medium Progress	ATW + 5%	84.1%
Higher Progress	=ATW	75.0%

Figure 7-4: Business Jet ATW Waypoints, ACA Entry Into Service and Energy Intensity Values

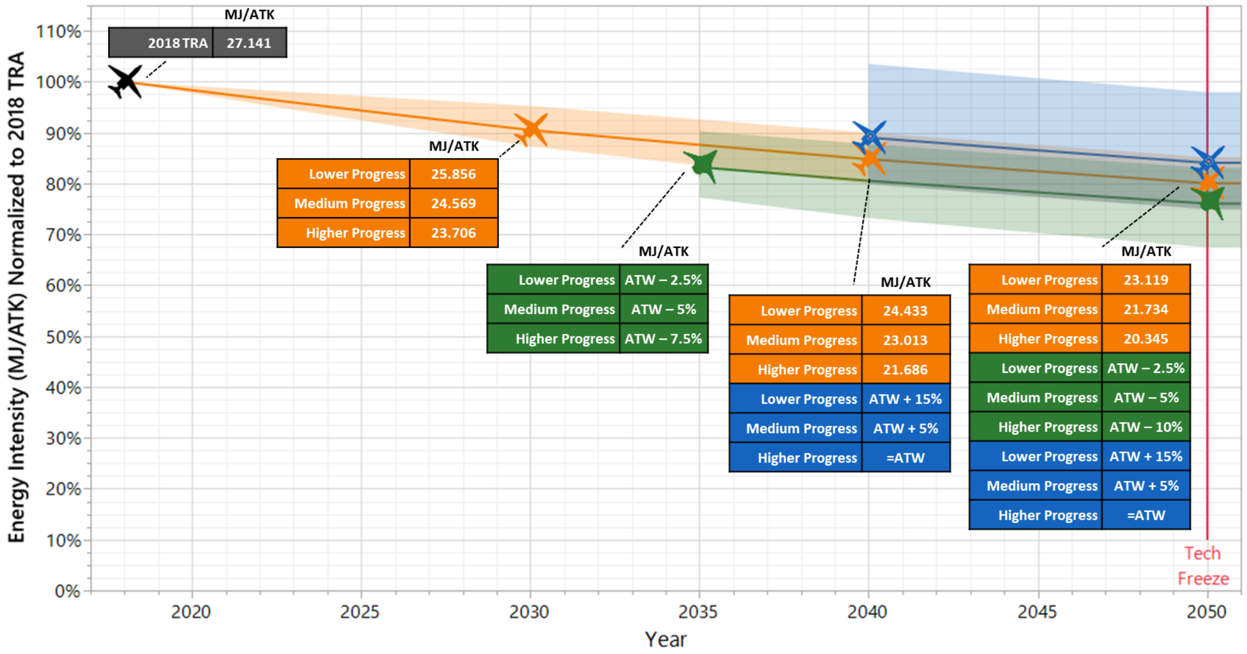


Figure 7-5: Business Jet Technology and Concept Energy Intensity Trend Normalized to the 2018 TRA

The market share table completes the input to MDG and is given in Table 7-8 and Figure 7-6. By 2050, it is forecast that the majority of the market share will switch to ACAs for both IS2 and IS3. Market share figures are rounded to the nearest 5% in the future years consistent with FESG process and assumptions.

Table 7-8: Business Jet Market Shares for New Entry and Replacements

Market Share for New Deliveries		Business Jet					
		2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	65%	40%	10%	0%
	ACA-T2			35%	60%	90%	100%
IS3	ATW-T1	100%	100%	65%	20%	10%	0%
	ACA-T2			30%	40%	45%	50%
	ACA-T3			5%	40%	45%	50%

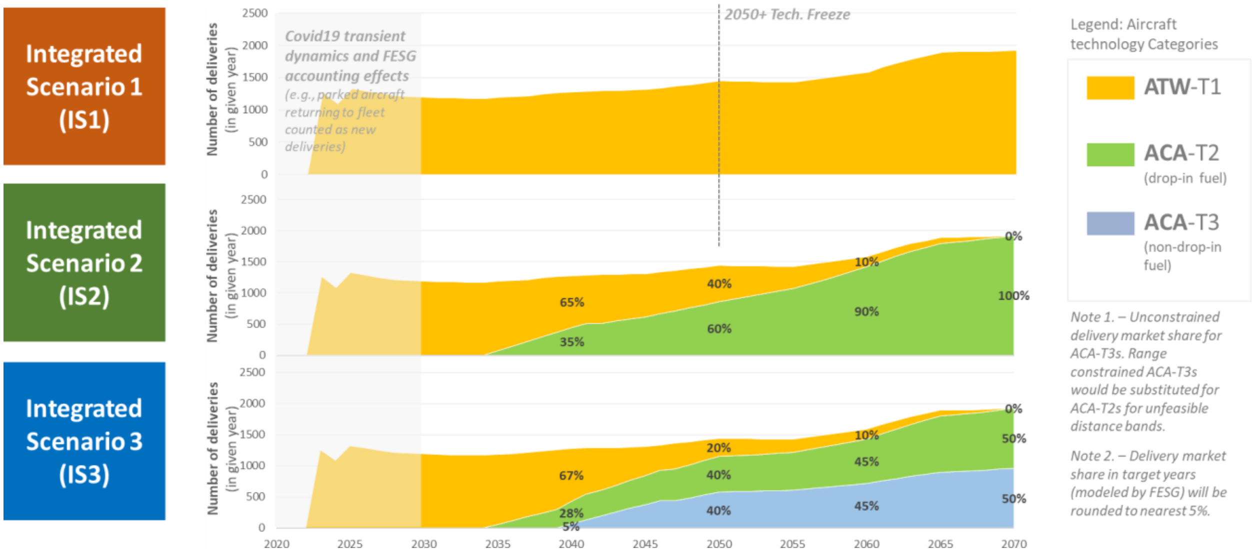


Figure 7-6: Market Share Timeline for Business Jet Class of Vehicles

7.5 REGIONAL JET INPUT FOR FLEET-WIDE MODELING

Regional jet energy intensity input for the MDG is summarized in Table 7-9 and Table 7-10 below. The energy intensity tables are only summary results, and the full results are given in Appendix G.3. In the regional jet class of vehicles, about an 18% reduction of energy use is predicted by 2050 with the advanced tube and wing concepts. For detailed reduction calculations please refer to Table 5-4.

Table 7-9: Regional Jet ATW-T1 Energy Intensity at Each Waypoint Normalized to the TRA

Energy Intensity Relative to 2018 TRA			Regional Jet			
			2018	2030	2040	2050–2070
T1	ATW-T1	Lower Progress	100.00%	97.13%	91.35%	86.51%
		Medium Progress		93.45%	85.88%	82.15%
		Higher Progress		88.86%	81.65%	78.56%

The earliest a regional jet ACA-T2s to enter into service was forecast to be in 2035 with a likely improvement over the contemporary ATW of 5 to 15%. The band of the advantage is expected to grow by 2050 with a 20% improvement achievable with higher progress. The higher progress ACA-T2 impact was modeled as a continuous improvement between 2035 and 2050 similar to the continuous improvements between decades of ATW efficiency. ACA-T3 variants with non-drop-in fuels may be 5% more efficient to 20% less efficient than an ATW. Please refer to Section 6.4.3 for detailed discussion how the improvements were forecasted.

Table 7-10: Regional Jet ACA Energy Intensity Deltas from The Respective ATW-T1 of the Same Year

ACA Energy Intensity Change Relative to Same Year's ATW			Regional Jet			
			2018	2030	2035	2050–2070
T2	ACA-T2	Lower Progress	—	—	-5.00%	-5.00%
		Medium Progress	—	—	-10.00%	-10.00%
		Higher Progress	—	—	-15.00%	-20.00%
T3	ACA-T3	Lower Progress	—	—	20.00%	20.00%
		Medium Progress	—	—	15.00%	15.00%
		Higher Progress	—	—	-5.00%	-5.00%

The trend plots provided in Figure 7-7 and Figure 7-8 are alternative representations of the tabular data with including uncertain progress bands. Figure 7-7 combines the entry into service and technology impacts of new entries. Figure 7-8 visualizes the relative scale of the uncertainties in the future years compared to the median expected progress. As seen on the plot, there is significant uncertainty in the efficiency of a non-drop-in variant of the regional jet. Energy intensity of the hydrogen-powered regional jet may be higher than the tube and wing aircraft that are flying today. For regional jet ACA-T3s to have a positive environmental impact, their fuel must be created in significantly greener ways.

	MJ/ATK	Relative to TRA
2018 TRA	7.389	100.0%

	MJ/ATK	Relative to TRA
Lower Progress	7.177	97.1%
Medium Progress	6.906	93.5%
Higher Progress	6.566	88.9%

	MJ/ATK	Relative to TRA
Lower Progress	6.750	91.4%
Medium Progress	6.346	85.9%
Higher Progress	6.033	81.7%

	MJ/ATK	Relative to TRA
Lower Progress	ATW – 5%	89.5%
Medium Progress	ATW – 10%	80.6%
Higher Progress	ATW – 15%	72.4%
Lower Progress	ATW + 20%	113.0%
Medium Progress	ATW + 15%	103.0%
Higher Progress	ATW – 5%	80.9%

	MJ/ATK	Relative to TRA
Lower Progress	6.393	86.5%
Medium Progress	6.071	82.2%
Higher Progress	5.805	78.6%
Lower Progress	ATW – 5%	82.2%
Medium Progress	ATW – 10%	73.9%
Higher Progress	ATW – 20%	62.8%
Lower Progress	ATW + 20%	103.8%
Medium Progress	ATW + 15%	94.5%
Higher Progress	ATW – 5%	74.6%

Figure 7-7: Regional Jet ATW Waypoints, ACA Entry Into Service and Energy Intensity Values

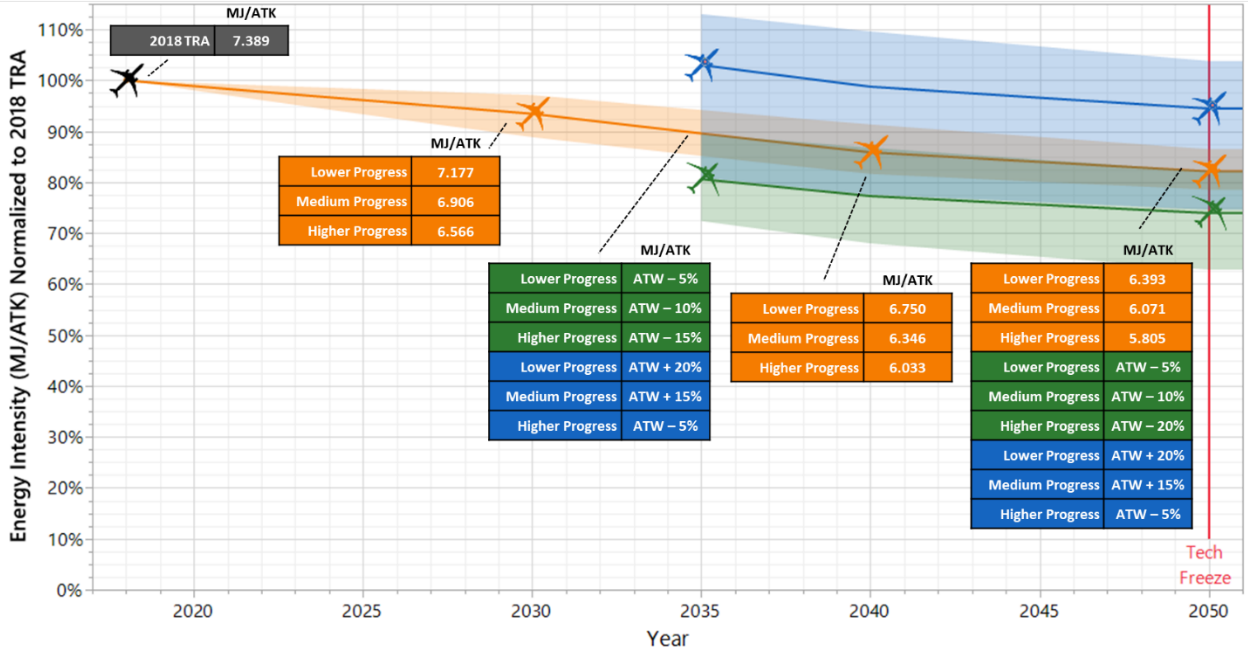


Figure 7-8: Regional Jet Technology and Concept Energy Intensity Trend Normalized to the 2018 TRA

The market share table completes the input to MDG and is given in Table 7-11 and Figure 7-9. By 2050, it is forecast that the majority of the market share will switch to ACAs for both IS2 and IS3. The cross-over point will be between 2040 and 2050. Market share figures are rounded to the nearest 5% in the future years consistent with FESG process and assumptions.

Table 7-11: Regional Jet Market Shares for New Entry and Replacements

Market Share for New Deliveries		Regional Jet					
		2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	65%	40%	10%	0%
	ACA-T2			35%	60%	90%	100%
IS3	ATW-T1	100%	100%	40%	20%	10%	0%
	ACA-T2			30%	40%	45%	50%
	ACA-T3			30%	40%	45%	50%

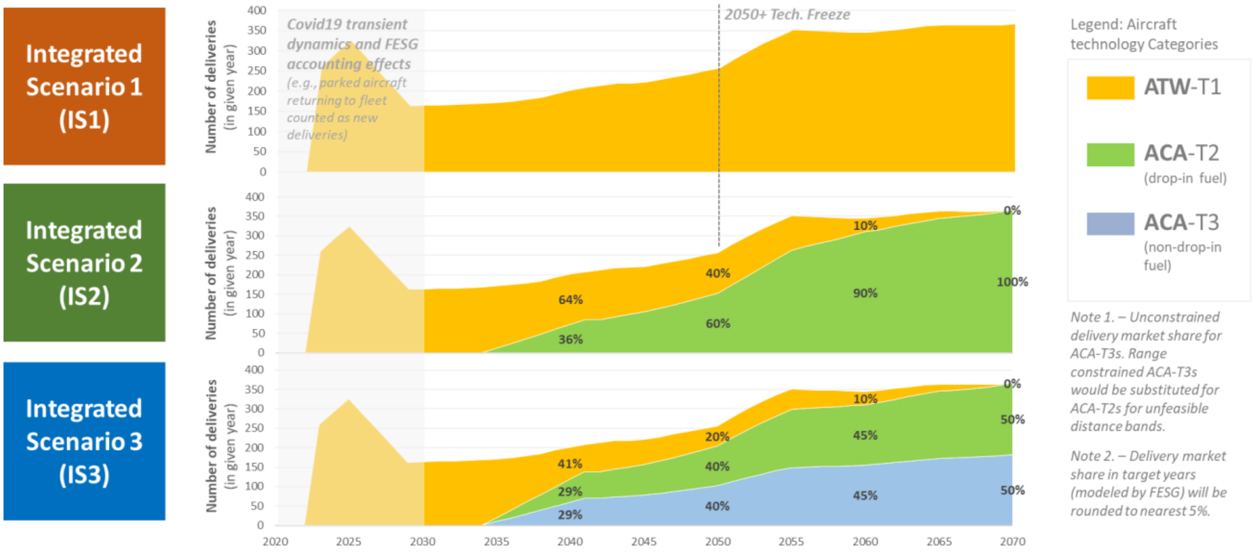


Figure 7-9: Market Share Timeline for Regional Jet Class of Vehicles

7.6 NARROW BODY INPUT FOR FLEET-WIDE MODELING

Narrow body energy intensity input for the MDG is summarized in Table 7-12 and Table 7-13 below. The energy intensity tables are only summary results, and the full results are given in Appendix G.4. In the narrow body class of vehicles, about an 24% reduction of energy use is predicted by 2050 with the advanced tube and wing concepts. For detailed reduction calculations please refer to Table 5-5.

Table 7-12: Narrow Body ATW-T1 Energy Intensity at Each Waypoint Normalized to the TRA

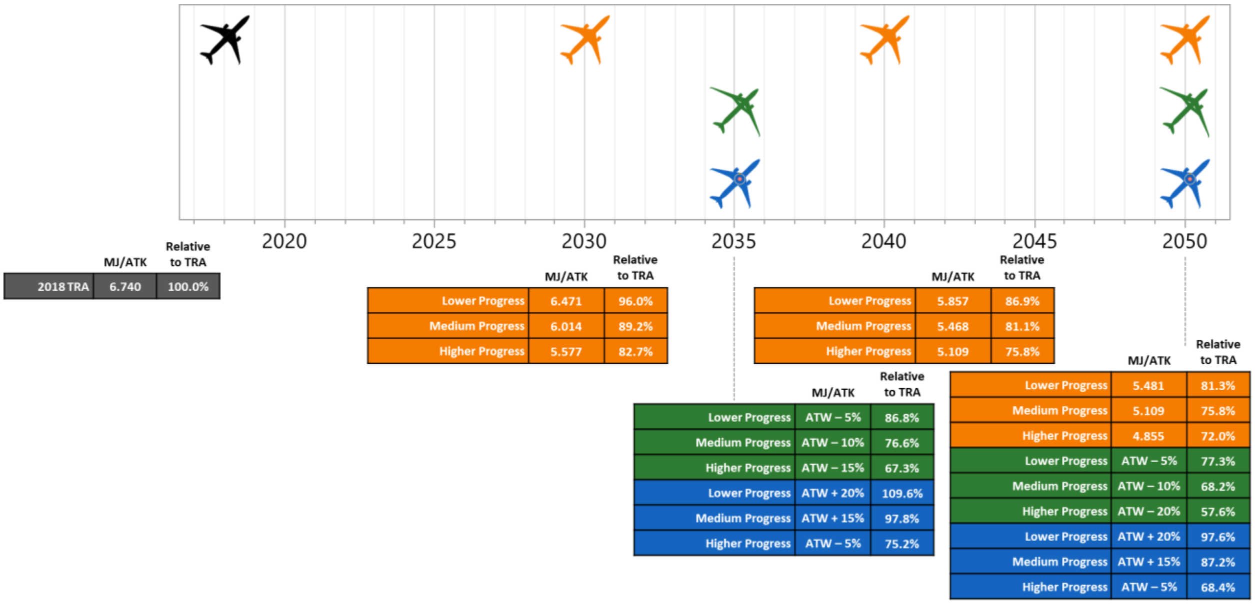
Energy Intensity Relative to 2018 TRA			Narrow Body			
			2018	2030	2040	2050–2070
T1	ATW-T1	Lower Progress	100.00%	96.01%	86.90%	81.32%
		Medium Progress		89.22%	81.13%	75.80%
		Higher Progress		82.74%	75.79%	72.03%

The earliest a narrow body ACA-T2s to enter into service was forecast to be in 2035 with a likely improvement over the contemporary ATW of 5 to 15%. The band of the advantage is expected to grow by 2050 with a 20% improvement achievable with higher progress. The higher progress ACA-T2 impact was modeled as a continuous improvement between 2035 and 2050 similar to the continuous improvements between decades of ATW efficiency. ACA-T3s may enter into service around the same time as the ACA-T2s. ACA-T3 variants with non-drop-in fuels may be 5% more efficient to 20% less efficient than an ATW. Please refer to Section 6.4.4 for detailed discussion how the improvements were forecasted.

Table 7-13: Narrow Body ACA Energy Intensity Deltas from The Respective ATW-T1 of the Same Year

ACA Energy Intensity Change Relative to Same Year's ATW			Narrow Body			
			2018	2030	2035	2050–2070
T2	ACA-T2	Lower Progress	—	—	-5.00%	-5.00%
		Medium Progress	—	—	-10.00%	-10.00%
		Higher Progress	—	—	-15.00%	-20.00%
T3	ACA-T3	Lower Progress	—	—	20.00%	20.00%
		Medium Progress	—	—	15.00%	15.00%
		Higher Progress	—	—	-5.00%	-5.00%

The trend plots provided in Figure 7-10 and Figure 7-11 are alternative representations of the tabular data with including uncertain progress bands. Figure 7-10 combines the entry into service and technology impacts of new entries. Figure 7-11Figure 7-8 visualizes the relative scale of the uncertainties in the future years compared to the median expected progress. As seen on the plot, there is significant uncertainty in the efficiency of a non-drop-in variant of the narrow body. Energy intensity of the first generation of hydrogen-powered narrow body may be higher than the tube and wing aircraft that are flying today. For narrow body ACA-T3s to have a meaningful positive environmental impact, their fuel must be created in significantly greener ways.



	MJ/ATK	Relative to TRA
2018 TRA	6.740	100.0%

	MJ/ATK	Relative to TRA
Lower Progress	6.471	96.0%
Medium Progress	6.014	89.2%
Higher Progress	5.577	82.7%

	MJ/ATK	Relative to TRA
Lower Progress	ATW – 5%	86.8%
Medium Progress	ATW – 10%	76.6%
Higher Progress	ATW – 15%	67.3%
Lower Progress	ATW + 20%	109.6%
Medium Progress	ATW + 15%	97.8%
Higher Progress	ATW – 5%	75.2%

	MJ/ATK	Relative to TRA
Lower Progress	5.857	86.9%
Medium Progress	5.468	81.1%
Higher Progress	5.109	75.8%

	MJ/ATK	Relative to TRA
Lower Progress	5.481	81.3%
Medium Progress	5.109	75.8%
Higher Progress	4.855	72.0%
Lower Progress	ATW – 5%	77.3%
Medium Progress	ATW – 10%	68.2%
Higher Progress	ATW – 20%	57.6%
Lower Progress	ATW + 20%	97.6%
Medium Progress	ATW + 15%	87.2%
Higher Progress	ATW – 5%	68.4%

Figure 7-10: Narrow Body ATW Waypoints, ACA Entry Into Service and Energy Intensity Values

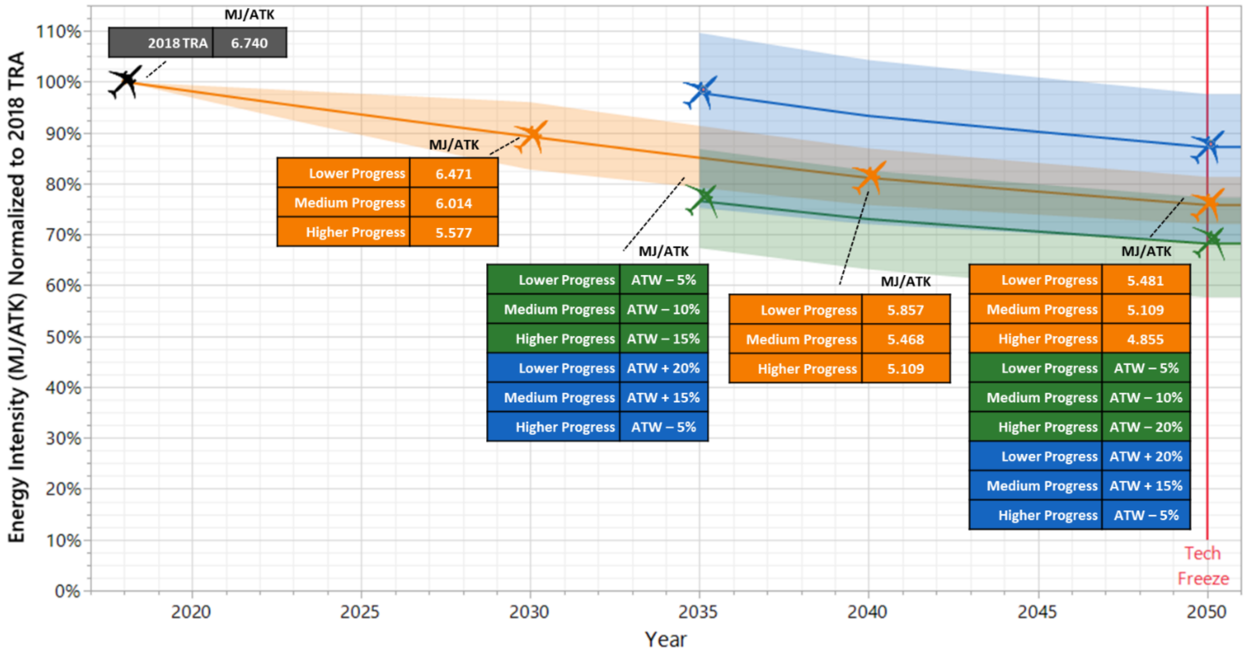
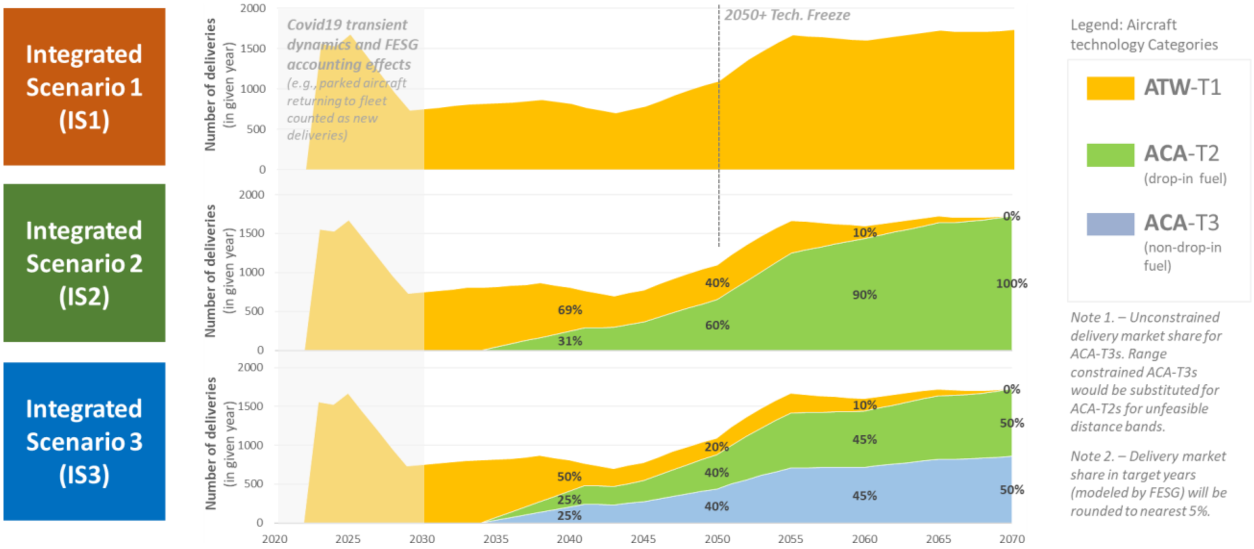


Figure 7-11: Narrow Body Technology and Concept Energy Intensity Trend Normalized to the 2018 TRA

The market share table completes the input to MDG and is given in Table 7-14 and Figure 7-12. By 2050, it is forecast that the majority of the market share will switch to ACAs for both IS2 and IS3. The cross-over point will be between 2040 and 2050. Market share figures are rounded to the nearest 5% in the future years consistent with FESG process and assumptions.

Table 7-14: Narrow Body Market Shares for New Entry and Replacements

Market Share for New Deliveries		Narrow Body					
		2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	70%	40%	10%	0%
	ACA-T2			30%	60%	90%	100%
IS3	ATW-T1	100%	100%	50%	20%	10%	0%
	ACA-T2			25%	40%	45%	50%
	ACA-T3			25%	40%	45%	50%



Note 1. – Unconstrained delivery market share for ACA-T3s. Range constrained ACA-T3s would be substituted for ACA-T2s for unfeasible distance bands.

Note 2. – Delivery market share in target years (modeled by FESG) will be rounded to nearest 5%.

Figure 7-12: Market Share Timeline for Narrow Body Class of Vehicles

7.7 WIDE BODY INPUT FOR FLEET-WIDE MODELING

Wide body energy intensity input for the MDG is summarized in Table 7-15 and Table 7-16 below. The energy intensity tables are only summary results, and the full results are given in Appendix G.5. In the wide body class of vehicles, about an 28% reduction of energy use is predicted by 2050 with the advanced tube and wing concepts. For detailed reduction calculations please refer to Table 5-6.

Table 7-15: Wide Body ATW-T1 Energy Intensity at Each Waypoint Normalized to the TRA

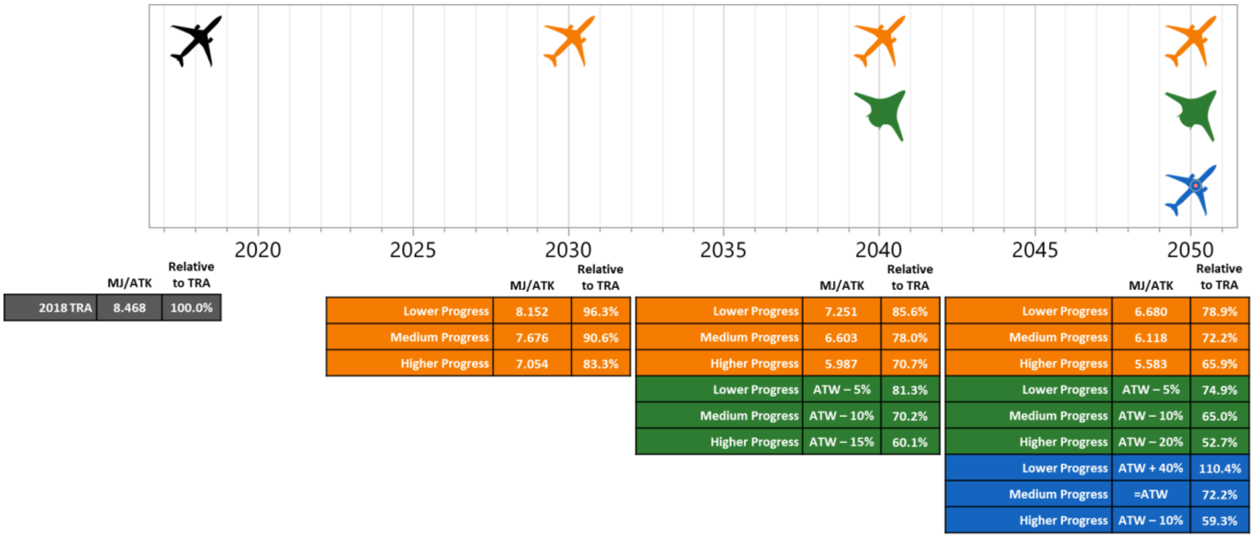
Energy Intensity Relative to 2018 TRA			Wide Body			
			2018	2030	2040	2050–2070
T1	ATW-T1	Lower Progress	100.00%	96.27%	85.62%	78.89%
		Medium Progress		90.65%	77.98%	72.24%
		Higher Progress		83.30%	70.70%	65.93%

The earliest a wide body ACA-T2s to enter into service was forecast to be in 2040 with a likely improvement over the contemporary ATW of 5 to 15%. The band of the advantage is expected to grow by 2050 with a 20% improvement achievable with higher progress. The higher progress ACA-T2 impact was modeled as a continuous improvement between 2035 and 2050 similar to the continuous improvements between decades of ATW efficiency. ACA-T3s are not expected to enter into service before 2050 due to the difficulties with making non-drop-in fuels feasible for longer range aircraft. ACA-T3 variants with non-drop-in fuels may be 10% more efficient to 40% less efficient than an ATW. Please refer to Section 6.4.5 for detailed discussion how the improvements were forecasted.

Table 7-16: Wide Body ACA Energy Intensity Deltas from The Respective ATW-T1 of the Same Year

ACA Energy Intensity Change Relative to Same Year's ATW			Wide Body			
			2018	2030	2040	2050–2070
T2	ACA-T2	Lower Progress			-5.00%	-5.00%
		Medium Progress			-10.00%	-10.00%
		Higher Progress			-15.00%	-20.00%
T3	ACA-T3	Lower Progress				40.00%
		Medium Progress				=ATW
		Higher Progress				-10.00%

The trend plots provided in Figure 7-13 and Figure 7-14 are alternative representations of the tabular data with including uncertain progress bands. Figure 7-13 combines the entry into service and technology impacts of new entries. Figure 7-14Figure 7-8 visualizes the relative scale of the uncertainties in the future years compared to the median expected progress. As seen on the plot, there is significant uncertainty in the efficiency of a non-drop-in variant of the wide body even in 2050. Energy intensity of the first generation of hydrogen-powered wide body in 2050 may be higher than the tube and wing aircraft that are flying today. For wide body ACA-T3s to have a meaningful positive environmental impact, their fuel must be created in significantly greener ways.



	MJ/ATK	Relative to TRA
2018 TRA	8.468	100.0%

	MJ/ATK	Relative to TRA
Lower Progress	8.152	96.3%
Medium Progress	7.676	90.6%
Higher Progress	7.054	83.3%

	MJ/ATK	Relative to TRA
Lower Progress	7.251	85.6%
Medium Progress	6.603	78.0%
Higher Progress	5.987	70.7%
Lower Progress	ATW – 5%	81.3%
Medium Progress	ATW – 10%	70.2%
Higher Progress	ATW – 15%	60.1%

	MJ/ATK	Relative to TRA
Lower Progress	6.680	78.9%
Medium Progress	6.118	72.2%
Higher Progress	5.583	65.9%
Lower Progress	ATW – 5%	74.9%
Medium Progress	ATW – 10%	65.0%
Higher Progress	ATW – 20%	52.7%
Lower Progress	ATW + 40%	110.4%
Medium Progress	=ATW	72.2%
Higher Progress	ATW – 10%	59.3%

Figure 7-13: Wide Body ATW Waypoints, ACA Entry Into Service and Energy Intensity Values

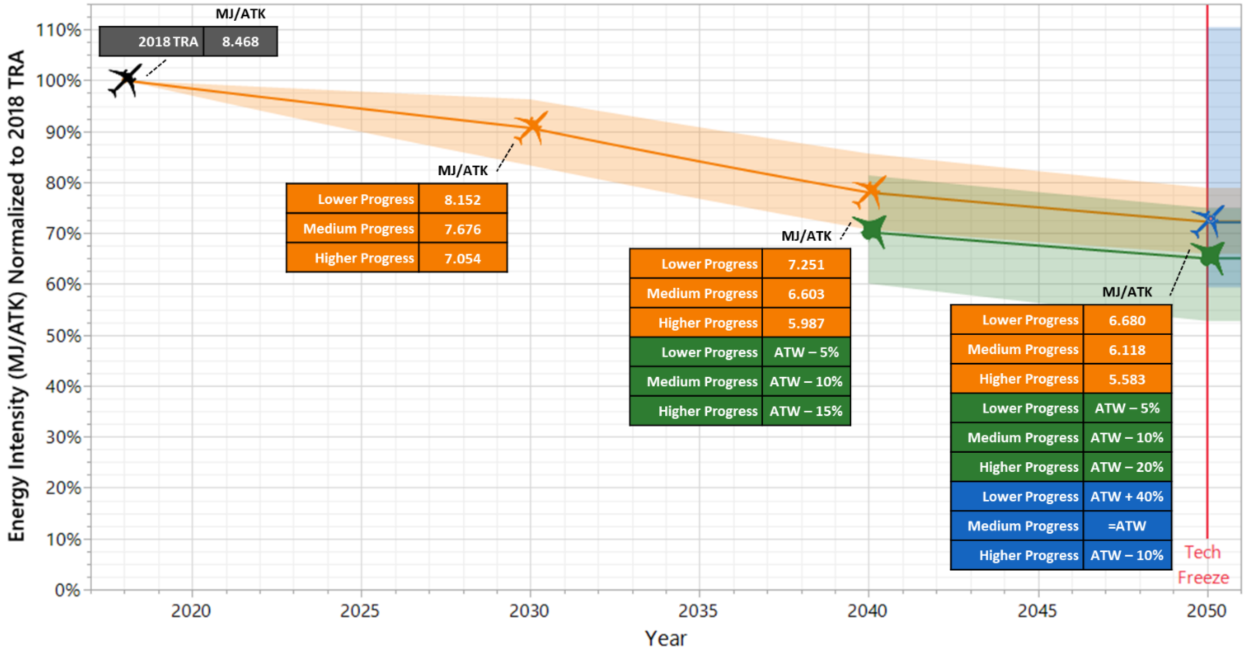
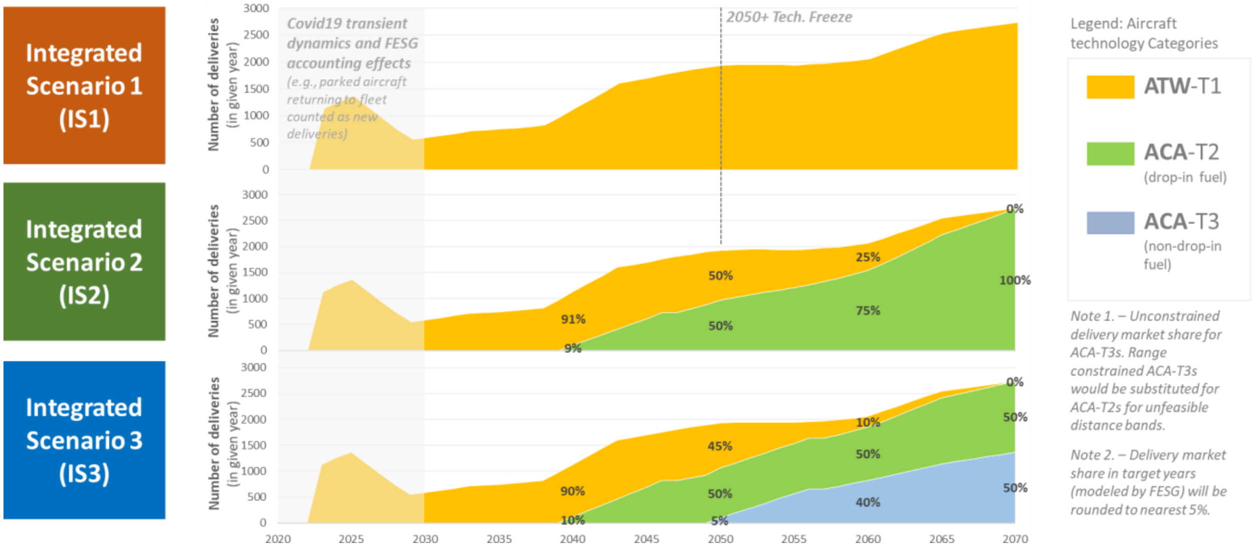


Figure 7-14: Wide Body Technology and Concept Energy Intensity Trend Normalized to the 2018 TRA

The market share table completes the input to MDG and is given in Table 7-17 and Figure 7-15. In the second integrated scenario, by 2050, it is forecast that the market share split will be about equal for ATWs and ACA-T2. For IS3, by 2050, ATWs will fall behind the collective ACA-T2 and ACA-T3s. The cross-over point for ACA-T3 to command a larger market share will be between 2050 and 2060 pending aircraft performance, acceptance, fuel availability, and costs associated with flying with non-drop-in fuels. Market share figures are rounded to the nearest 5% in the future years consistent with FESG process and assumptions.

Table 7-17: Wide Body Market Shares for New Entry and Replacements

Market Share for New Deliveries		Wide Body					
		2018	2030	2040	2050	2060	2070
IS1	ATW-T1	100%	100%	100%	100%	100%	100%
IS2	ATW-T1	100%	100%	95%	50%	25%	0%
	ACA-T2			5%	50%	75%	100%
IS3	ATW-T1	100%	100%	95%	45%	10%	0%
	ACA-T2			5%	50%	50%	50%
	ACA-T3				5%	40%	50%



Note 1. – Unconstrained delivery market share for ACA-T3s. Range constrained ACA-T3s would be substituted for ACA-T2s for unfeasible distance bands.

Note 2. – Delivery market share in target years (modeled by FESG) will be rounded to nearest 5%.

Figure 7-15: Market Share Timeline for Wide Body Class of Vehicles

ANNEX A. TECHNOLOGY READINESS LEVEL DEFINITIONS

The TRL scale is used worldwide as a means for analyzing and communicating the maturity of technologies and systems under development. TRL captures the type of experimentation that has been performed on a given entity, including details of the experimental environment, test article, and test purpose. There are nine total levels in the TRL scale, and they are:

- TRL 1 = Basic principles observed and reported
- TRL 2 = Technology concept and/or application formulated
- TRL 3 = Analytical and experimental critical function
- TRL 4 = Component and/or breadboard test in laboratory environment
- TRL 5 = Component and/or breadboard verification in relevant environment
- TRL 6 = System/subsystem model or prototype demonstration/validated in a relevant environment
- TRL 7 = System prototype demonstration in flight environment
- TRL 8 = Actual system completed and “flight qualified” through test and demonstration
- TRL 9 = Actual system "flight proven" on operational flight

ANNEX B. ENVIRONMENTAL DESIGN SPACE COMPONENTS

B.1 INTRODUCTION

This Appendix provides a further discussion of the components of the Environmental Design Space (EDS); the modeling and simulation environment utilized to assess the technology baskets for the IEIR goal study. EDS is comprised of a number of NASA developed analysis tools for the evaluation of the engine and airframe performance characteristics. Each of the tools are described herein with the connectivity of the tools described in later sections.

B.2 CMPGEN

CMPGEN is a NASA Glenn analysis tool used to generate component maps for the fan, LPC, and HPC [62]. The user-defined inputs for each component include the design point pressure ratio, the corrected flow, corrected flow per area, and stall margin. The program uses these design point values along with built-in empirical relationships to calculate off-design data for corrected flow, efficiency, and pressure ratio as a function of corrected speed and pressure ratio. The ranges of corrected speed and pressure ratio for use in component map generation are also specified by the user.

B.3 NUMERICAL PROPULSION SYSTEM SIMULATION (NPSS)

The Numerical Propulsion System Simulation (NPSS) is an aerothermal-mechanical computer simulation that is capable of modeling physical interactions within an engine model. NPSS is under continuing development by the NPSS Consortium, hosted at Southwest Research Institute and is supported by the U.S. aeropropulsion industry and the Department of Defense in hopes of lowering concept-to-production development time and reducing the need for full-scale tests or more sophisticated analysis tools [63,' 64]. Version 1.6.5v is currently integrated into EDS. NPSS is an object-oriented simulator which performs steady state and transient off-design performance prediction by calling upon a number of varying fidelity tools which are controlled using the NPSS solution algorithm. At this time, NPSS offers the following capabilities:

- Complete model definition through input files(s)
- NIST (National Institute of Standards and Technology) compliant thermodynamic gas-properties package
- Analytical solver with auto-setup, constraints, and discontinuity handling
- Steady-state and transient system simulation
- Flexible report generation
- Built-in object-oriented programming language for user-definable components and functions
- Support for distributed running of external code(s)
- Support for test data matching analysis

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62 Converse, G.L.; and Giffin, R.G., “Extended Parametric Representation of Compressors Fans and Turbines. Vol. I - CMGEN User's Manual,” NASA CR-174645, 1984.

63 “NPSS User Guide.” Software Release: NPSS_1.6.4; REV: Q; Doc. #: NPSS–User; Doc Revision: W in progress; Revision Date: November 5, 2006.

64 “NPSS Reference Sheets.” Software Release: NPSS_1.6.4 V; Doc. #: NPSS–Ref Sheets; Doc Revision: W in progress; Revision Date: January 05, 2007.

B.4 WEIGHT ANALYSIS OF TURBINE ENGINES (WATE)

Weight Analysis of Turbine Engines (WATE) was developed by the Boeing Military Airplane Development group as a subprogram for the NASA Engine Performance Program (NEPP) in 1979 in an effort to provide weight and dimension estimates for propulsion systems for use in conceptual design. EDS currently utilizes an updated version, WATE++, which has been moved to the same language as NPSS. WATE++ [65] estimates the weight and dimensions of both large and small gas turbine engines. Approximations made within WATE++ are based on historical correlations, material properties, geometric characteristics, and component parameter information. Sizes and weights for the inlet, fan, compressor, turbine, burner, mixers, nozzles, ducts, splitters, and valves are calculated.

B.5 FLIGHT OPTIMIZATION SYSTEM (FLOPS)

The FLight OPtimization System (FLOPS) is a multidisciplinary computer program developed for conceptual and preliminary design and evaluation of advanced aircraft concepts [66]. EDS currently runs FLOPS version 8.11, which consists of eight modules:

- Weights, aerodynamics
- Engine cycle analysis – Not utilized for EDS
- Propulsion data scaling and interpolation
- Mission performance
- Takeoff and landing
- Noise – Not utilized for EDS
- Cost analysis – Not utilized for EDS
- Program control

Through the program control module, FLOPS may be used to analyze a point design, parametrically vary certain design variables, or optimize a configuration. The weights and aerodynamics modules use statistical and empirical methods to estimate respective metrics, i.e. component weights and aerodynamic performance. The engine cycle analysis module is based on a modified version of NEPCOMP designated QNEP. This module is capable of internally generating an engine deck (thrust, fuel flow, etc.) at various Mach-altitude combinations. Following the engine deck module, the propulsion module sizes the engine by making use of scaling laws. The mission performance module takes the information calculated in the previous modules and determines the performance characteristics of the aircraft. The takeoff and landing module calculates the requirements necessary to meet the performance demands at takeoff and landing and with the available data calculated attempts to ensure that the aircraft meets all FAR 25 requirements. The noise footprint module based on the FOOTPR program generates takeoff and climbout profiles for the aircraft and computes the noise footprint contour data and/or noise levels at user specified or FAA locations. From the cost analysis module, discussed in more detail in the next section, the airframe RDT&E and production cost, engine RDT&E and production costs and direct and indirect operating costs are estimated to provide a life cycle cost for subsonic transport aircraft. Most of the input data required for these modules is contained in a Namelist formatted input file. Many values have default settings to provide reference values for new users. FLOPS also has the capability of using data from external tools, specifically engine performance decks, and higher fidelity weight and aerodynamic prediction tools. In lieu of the internal engine deck generation capabilities, EDS generates the performance deck within NPSS and the propulsion weight and dimensions in WATE++ and passes the data to FLOPS.

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65 Tong, M., Naylor, B., "An Object-Oriented Computer Code for Aircraft Engine Weight Estimation," NASA/TM-2009-215656.

66 "Flight Optimization System, Release 8.11, User's Guide." L. A. (Arnie) McCullers, Revised 9 October 2009.

B.6 AIRCRAFT NOISE PREDICTION PROGRAM (ANOPP)

The NASA Aircraft Noise Prediction Program (ANOPP) [67, 68] was developed by the NASA Langley Research Center and provides a capability to predict noise from aircraft in flight, accounting for the effects of the aircraft configuration, its airframe, its engines, its operations, and the atmosphere. This is accomplished by computing the source noise from each aircraft component that comprises the engine and airframe and propagating these results through the atmosphere to far-field observers. ANOPP computes the acoustic power of aircraft noise sources as a function of polar and azimuthal angles, frequency, and time along a user defined flight path. The observer receives the noise signal from the direct ray and, for observers above the ground, can also receive a ray reflected by the local ground surface. The noise source models in ANOPP have been developed over decades and largely represent semi-empirical and empirical models for a wide range of aircraft technologies. An analytical method based on Fresnel diffraction theory is also included to provide an initial prediction of the effects of shielding and reflection. User defined tables of data can be input to directly represent the effects of noise reduction technologies or other effects. New noise source models continue to be developed to provide better prediction of future aircraft technology. In addition, new modeling development continues to provide more general methods for the effects related to propulsion airframe aeroacoustic interactions including from shielding and reflection.

The outputs from ANOPP are divided in two main groups: certification noise levels and noise power distance curves. The first are calculated using the geometric and cycle information of the engine from NPSS and the trajectory provided by FLOPS, which ANOPP uses to define where to start the propagation of the noise produced. ANOPP then calculates the noise perceived at the 3 certification observers, following FAR part 36 requirements. ANOPP calculates the effective perceived noise levels for each individual component, as well as the overall aircraft noise level. The NPD's are calculated in a similar way, but only for the whole aircraft, not individual components. Instead of using a trajectory, ANOPP calculates the noise levels at different distances from the aircraft and at different thrust settings, for both approach and landing configurations.

B.7 EDS FUNDAMENTAL ARCHITECTURE

The fundamental architecture of EDS is based on a multiple point design (MPD) for the engine based on airframe thrust requirements and a design loop is iterated until convergence is reach between the engine capability and airframe requirements. The base logic for EDS revolves around NPSS simultaneously solving four design points. The Aero Design Point (ADP) is considered the component design point, with fan pressure ration (FPR), low pressure compressor pressure ratio (LPCPR), and high-pressure compressor pressure ratio (HPCPR) specified at this point. The bypass ratio (BPR) at the ADP is determined by specifying an Extraction Ratio. The ADP T4 is set by specifying a maximum T4 and an engine lapse rate. The airflow is determined by specifying the thrust required at top of climb (TOC). Turbine cooling flows are determined at the Takeoff condition (max T4). Design and Power Management variables are included in addition to variables provided by Auto Solver Setup for continuity and work balance. Finally, solver variables are added to specify the scaling points for the fan and compressor maps and to determine the turbine cooling flows using the Coolit algorithm [69]. The independent variables used for convergence in

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67 Lopes, L.V., Burley, C.L., "ANOPP2 User's Manual, Version 1.2", NASA/TM-2016-219342, October 2016.

68 William E. Zorumski, "Aircraft Noise Prediction Program Theoretical Manual", NASA Technical Memorandum 83199. Revised December 2006.

69 Gauntner, J., "Algorithm for Calculating Turbine Cooling Flow and the Resulting Decrease in Turbine Efficiency," NASA-TM-81453, 1980.

the MDP are provided by Schutte, while the flow of information is depicted in Figure B-1 [70]. The convergence criteria for the design case is a thrust and fuel balance of the engine and airframe.

The convergence architecture is based on the following logic:

- Generate initial component maps
- Perform the MPD based on an initial guess of the four thrust requirements
- Create engine flowpath
- Generate the engine performance deck through the flight envelope (Flt Env)
- Fly the aircraft through FLOPS to obtain actual thrust requirements at the four points
- Iterate until thrust available equals thrust required

Table B-1. EDS Multi-point Design List of Varied Independents

Parameter to Vary	To Satisfy
ADP BPR	ADP Extraction Ratio (= 1.0)
ADP Airflow	TOC Thrust
ADP FAR	ADP T4
TOC FAR	TOC Airflow
Takeoff FAR	Takeoff T4
SLS T4	SLS T4
Fan design point Rline	Fan design point surge margin
LPC design point Rline	LPC design point surge margin
HPC design point Rline	HPC design point surge margin
HPT vane percent flow	Coolit calculation at takeoff
HPT blade percent flow	Coolit calculation at takeoff
LPT vane percent flow	Coolit calculation at takeoff
LPT blade percent flow	Coolit calculation at takeoff

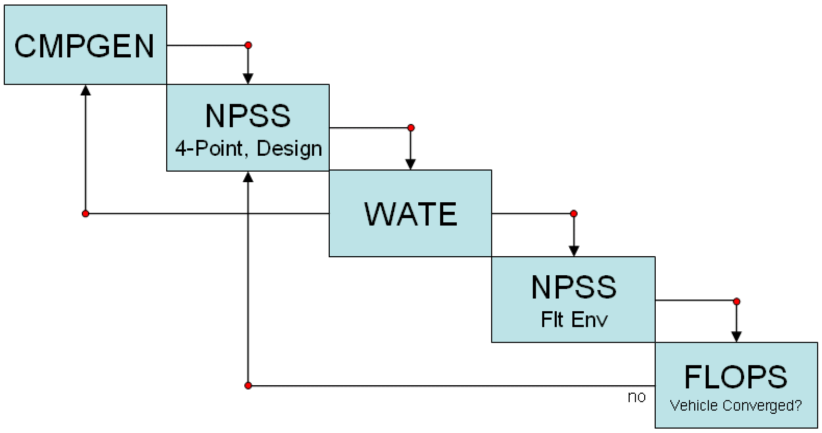

Figure B-1. EDS Vehicle Convergence Architecture

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[70] Schutte, J., Tai, J., Mavris, D., "Multi-Design Point Cycle Design Incorporation into the Environmental Design Space," 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, AIAA 2012-3812.

ANNEX C. TECHNOLOGY REFERENCE AIRCRAFT MODELING DETAILS

C.1 TURBOPROP TRA

C.1.1 Assumptions

TP Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

- Notional De Havilland Dash 8-400
- Assumed payload of 16,650 lbm (7,552 kg)
  - 74 pax at 225 lbm (including baggage) at design range
- Design range of 1,100 nm (2,040 km)
- Two three-spool engines, notional Pratt & Whitney Canada PW150A
  - Created model from publicly available information

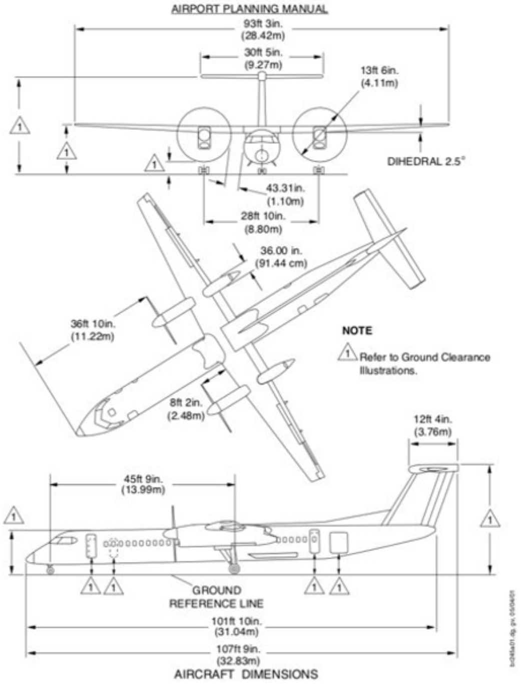
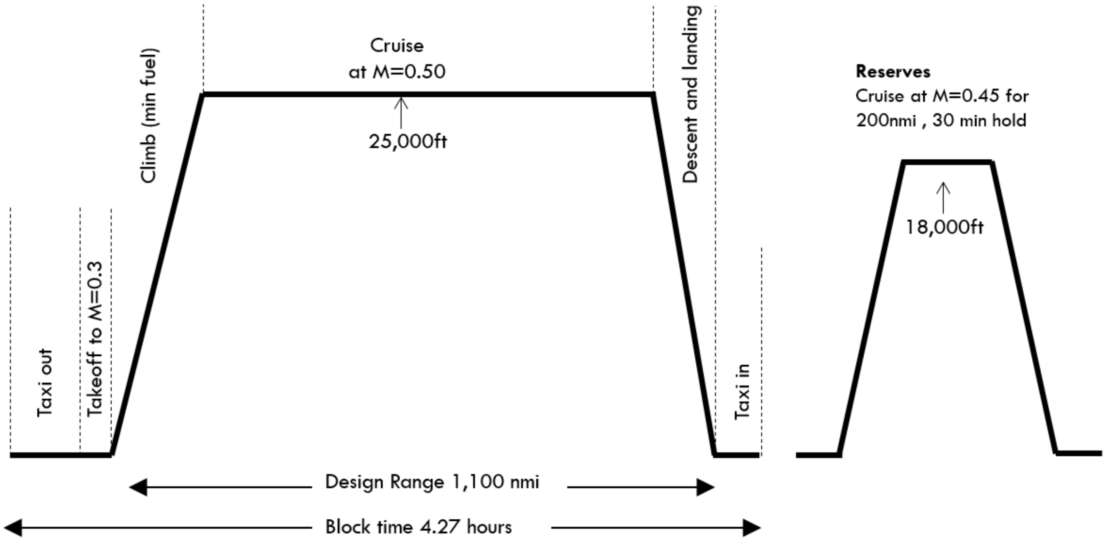


Figure 2 – 2

Image Ref: Bombardier, Q400 Airport Planning Manual
Values obtained or measured from this reference.

Description	Value
MTOW	65,200 lbs / 29,574 kg
Span	93.3 ft / 28.4 m
Wing Area	679 ft^2 / 63.1 m^2
Aspect Ratio	12.8
¼ Chord Sweep	5.98 deg
HT Area	179.3 ft^2 / 16.7 m^2
HT Span	33.6 ft / 10.2 m
HT Aspect Ratio	6.3
HT ¼ Chord Sweep	8.0 deg
VT Area	166 ft^2 / 15.4 m^2
VT Span	14.4 ft / 4.4 m
VT Aspect Ratio	1.25
VT ¼ Chord Sweep	29 deg
Fuselage Length	101.8 ft / 31.0 m
Fuselage Height	8.4 ft / 2.6 m
Fuselage Width	8.8 ft / 2.7 m

C.1.2 Mission Profile



C.1.3 Vehicle Performance

Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	63.3
Aspect ratio	AR	~	12.8
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.8
C_{Lmax} Take-off	C_{LmaxTO}	~	2.5
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.50
Design fuel	~	kg	3,413
Design Payload at R_2		kg	8,480
Design Range at R_2	R2	nm	750
Fuselage height	DF	m	2.6
Fuselage length	XL	m	31.0
Fuselage width	WF	m	2.7
Initial Cruise Altitude	~	ft	25,000
Landing field length	LdgFL	m	1,590
Manufacturer's empty weight	MEW	kg	16,558
Maximum L/D at cruise	~	~	16.68
Maximum landing mass	MLM	kg	26,162
Maximum SLS thrust per engine	F_n	kN	44.9
Maximum take-off mass	MTOM	kg	29,483
Number of passengers	# pax		74
Operating empty weight	OEW	kg	17,148
Overall pressure ratio (SLS)	OPR	~	17.97
Ramp gross weight	~	kg	29,665
Reference geometric factor	RGF	m^2	59.6
Service ceiling	~	ft	25,000
Shaft Horsepower (SLS)	SHP	hp	6,330
Take-off field length	TOFL	m	1,728
Wing area	SW	m^2	63.1

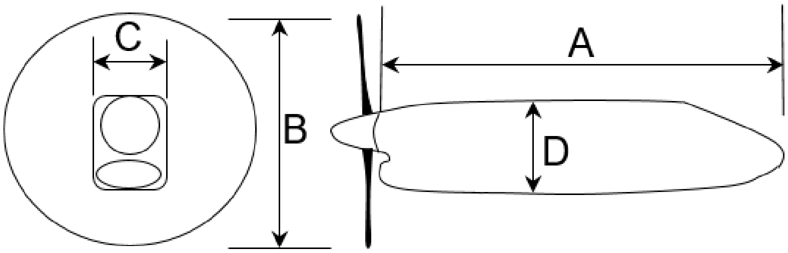
Wing span	~	m	28.4
Wing ¼ chord sweep	~	degrees	5.98

Mass and Balance Summary: Empty Weight Breakout	**lbs**	**kg**
WING	5984	2714
HORIZONTAL	813	369
VERTICAL TAIL	781	354
FUSELAGE	7878	3573
LANDING GEAR	3300	1497
NACELLE	1650	748
STRUCTURE TOTAL	20406	9256
ENGINES	4961	2250
FUEL SYSTEMS/ PLUMBING	494	224
PROPULSION TOTAL	5454	2474
SURFACE CONTROLS	1030	467
AUXILIARY POWER	489	222
ELECTRICAL & INSTRUMENTS	888	403
HYDRAULICS	484	220
AVIONICS	497	225
FURNISHINGS & MISC SYSTEMS	6451	2926
AIR CONDITIONING & ANTI-ICING	806	366
FIXED EQUIPMENT TOTAL	10645	4828

Mass and Balance Summary	**lbs**	**kg**
WEIGHT EMPTY	36505	16558
OPERATOR ITEMS	1299	589
OPERATING WEIGHT EMPTY (OWE)	37804	17148
PAYLOAD 74 Passengers + baggage (225 lbs each)	16650	7552
ZERO FUEL WEIGHT	54454	24700
TOTAL FUEL	10946	4965
TRIP FUEL **(TOTAL w/o RESERVES AND TAXI)**	45088	20452
RAMP GROSS WEIGHT	65400	29665
Taxi Out Fuel Weight	400	181
MAXIMUM TAKE-OFF WEIGHT	65000	29483
OEW/MTOW	0.582	0.582

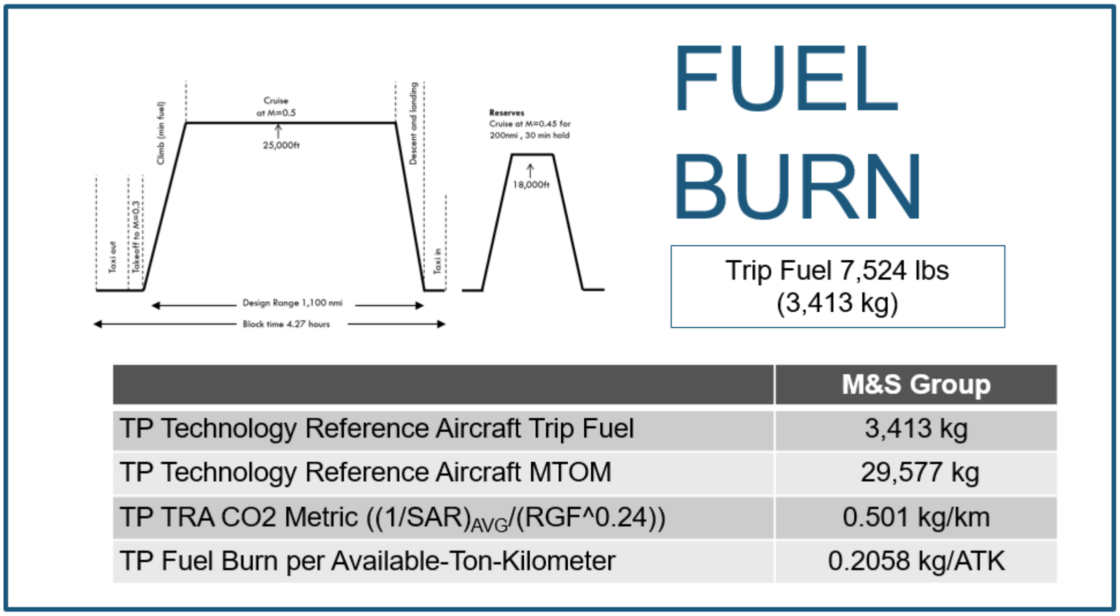
C.1.4 Engine Performance

Description	**Units**	**Value**
SLS Thrust	kN	44.9
Propeller Diameter (B)	m	4.1
Dry Weight	kg	717
Turbomachinery Arrangement	~	3-1-1-1-2
SFC @ beginning of cruise	lbm/hr/lbf	0.474
Max Nacelle Width (C)	m	0.90
Max Nacelle Height (D)	m	7.6
Max Nacelle Length (A)	m	5.2



Description	**Sea Level Static**	**Max Climb**	**Cruise**
Net Thrust (kN)	44.9	9.93	6.95
OPR	18.0	17.4	14.2
SHP (hp)	6,330	2,800	1,927

C.1.5 Top Level Metrics



FUEL
BURN

Trip Fuel 7,524 lbs
(3,413 kg)

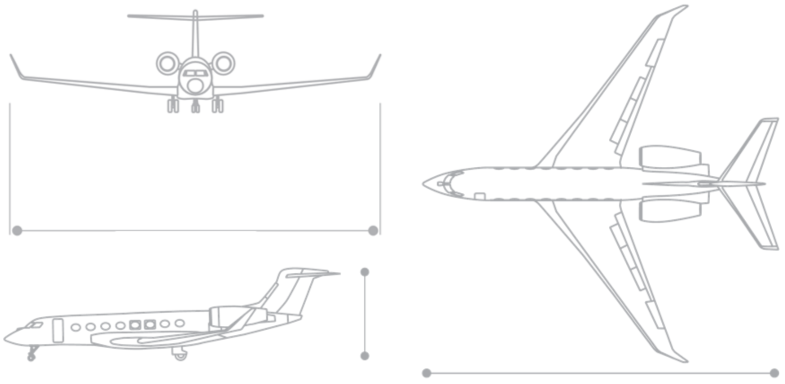
	M&S Group
TP Technology Reference Aircraft Trip Fuel	3,413 kg
TP Technology Reference Aircraft MTOM	29,577 kg
TP TRA CO2 Metric ((1/SAR)$_{AVG}$/(RGF^0.24))	0.501 kg/km
TP Fuel Burn per Available-Ton-Kilometer	0.2058 kg/ATK

C.2 BUSINESS JET TRA

C.2.1 Assumptions

BJ Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

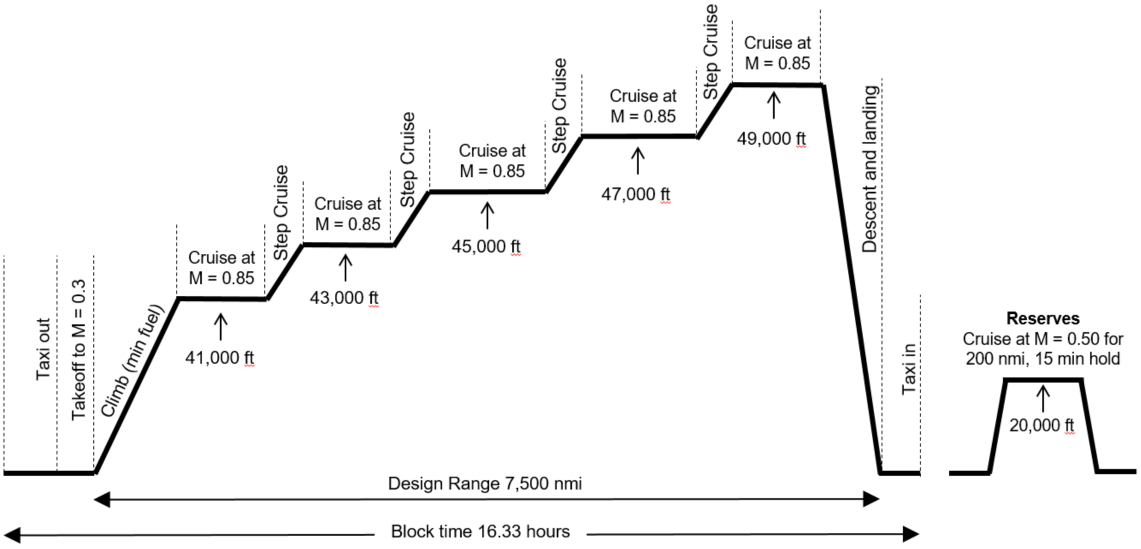
- Notional Gulfstream G650ER
- Assumed payload of 1,800 lbm (817 kg)
    - 8 passengers @ 225 lbm each (@ design range including baggage)
- Design range of 7,500 nm at M0.85
    - High speed mission range of 6,400 nmi with 6,500 lb of payload
- Metallic main components (wing, fuselage, empennage)
- 2 turbofan engines (notional Roll-Royce BR725 A1-12)
    - Created notional engine model from publically available information and ICAO databank
    - Match ICAO fuel flow and thrust levels



*Drawings not to scale
Images taken from http://www.gulfstream.com/images/uploads/brochures/aircraft/G650_Details_ENG.pdf

Description	Value
MTOW	103,600 lbs / 46,992 kg
Span	99.58 ft / 30.35 m
Wing Area	1283 ft^2 / 119.2 m^2
Aspect Ratio	7.23
¼ Chord Sweep	34.0 deg
HT Area	274.7 ft^2 / 25.52 m^2
HT Span	37.06 ft / 11.30 m
HT Aspect Ratio	5.0
HT ¼ Chord Sweep	31.0 deg
VT Area	150.22 ft^2 / 13.95 m^2
VT Span	12.13 ft / 3.70 m
VT Aspect Ratio	0.98
VT ¼ Chord Sweep	37.0 deg
Fuselage Length	87.6 ft / 26.7 m
Fuselage Height	8.4 ft / 2.56 m
Fuselage Width	9.0 ft / 2.74 m

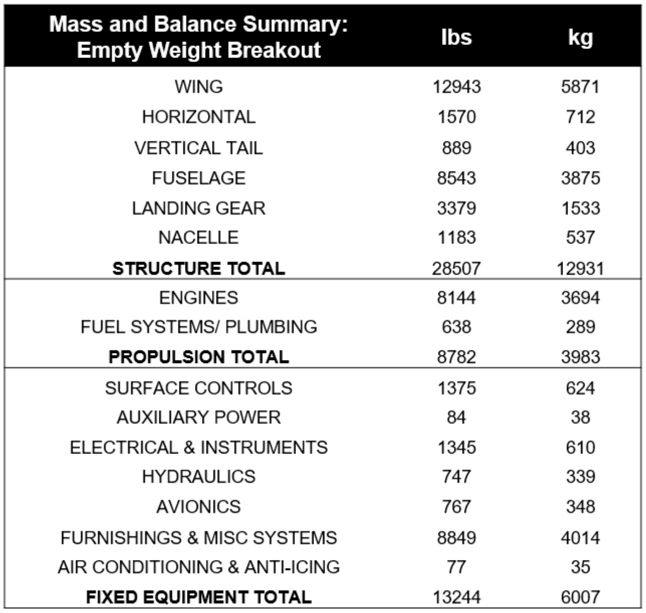
C.2.2 Mission Profile



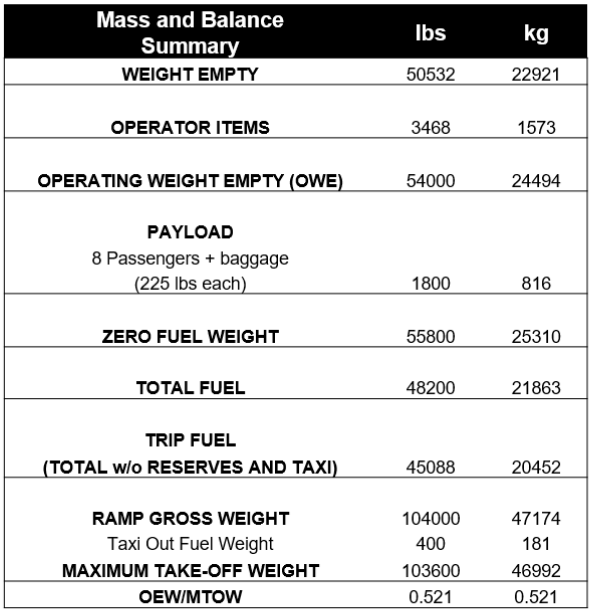
C.2.3 Vehicle Performance

Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	56.1
Aspect ratio	AR	~	7.23
Bypass ratio (SLS)	BPR	~	4.35
C_{Lmax} Landing	$C_{LmaxLdg}$	~	1.82
C_{Lmax} Take-off	C_{LmaxTO}	~	1.40
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.85
Design fuel	~	kg	20,504
Design Payload at R_2		kg	817
Design Range at R_2	R2	nm	7,500
Fuselage height	DF	m	2.56
Fuselage length	XL	m	26.7
Fuselage width	WF	m	2.74
Initial Cruise Altitude	~	ft	41,000
Landing field length	LdgFL	m	1,525
Manufacturer's empty weight	MEW	kg	22,921
Maximum L/D at cruise	~	~	18.98
Maximum landing mass	MLM	kg	25,308
Maximum SLS thrust per engine	F_n	kN	75.7
Maximum take-off mass	MTOM	kg	46,992
Number of passengers	# pax		8
Operating empty weight	OEW	kg	24,494
Overall pressure ratio (SLS)	OPR	~	26.15
Ramp gross weight	~	kg	47,174
Reference geometric factor	RGF	m^2	45.56
Service ceiling	~	ft	51,000
Take-off field length	TOFL	m	1,764
Wing area	SW	m^2	119.2

Wing span	~	m	30.35
Wing ¼ chord sweep	~	degrees	34.0



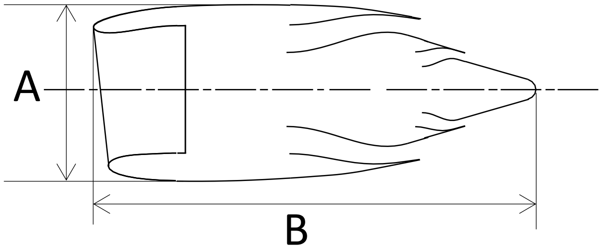
Mass and Balance Summary: Empty Weight Breakout	lbs	kg
WING	12943	5871
HORIZONTAL	1570	712
VERTICAL TAIL	889	403
FUSELAGE	8543	3875
LANDING GEAR	3379	1533
NACELLE	1183	537
STRUCTURE TOTAL	28507	12931
ENGINES	8144	3694
FUEL SYSTEMS/ PLUMBING	638	289
PROPULSION TOTAL	8782	3983
SURFACE CONTROLS	1375	624
AUXILIARY POWER	84	38
ELECTRICAL & INSTRUMENTS	1345	610
HYDRAULICS	747	339
AVIONICS	767	348
FURNISHINGS & MISC SYSTEMS	8849	4014
AIR CONDITIONING & ANTI-ICING	77	35
FIXED EQUIPMENT TOTAL	13244	6007



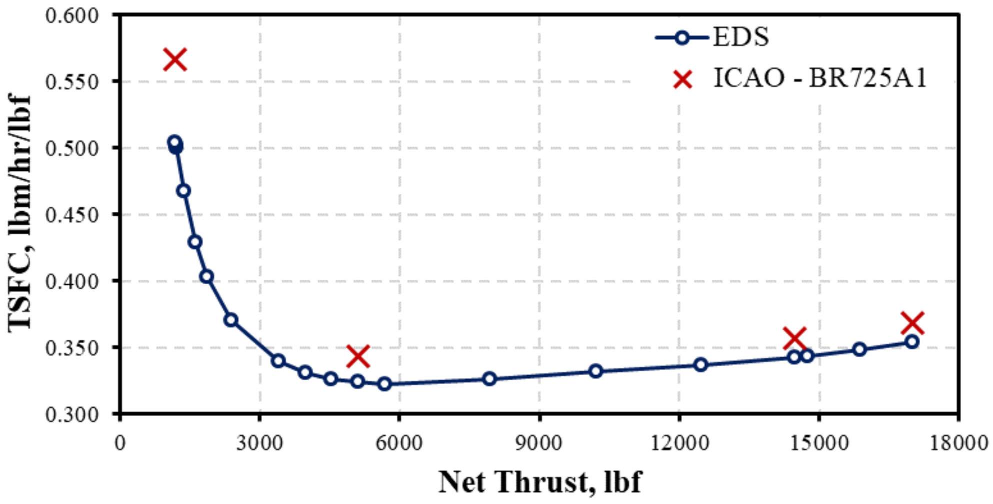
Mass and Balance Summary	lbs	kg
WEIGHT EMPTY	50532	22921
OPERATOR ITEMS	3468	1573
OPERATING WEIGHT EMPTY (OWE)	54000	24494
PAYLOAD 8 Passengers + baggage (225 lbs each)	1800	816
ZERO FUEL WEIGHT	55800	25310
TOTAL FUEL	48200	21863
TRIP FUEL (TOTAL w/o RESERVES AND TAXI)	45088	20452
RAMP GROSS WEIGHT	104000	47174
Taxi Out Fuel Weight	400	181
MAXIMUM TAKE-OFF WEIGHT	103600	46992
OEW/MTOW	0.521	0.521

C.2.4 Engine Performance

Description	Units	Value
SLS Thrust	kN	75.7
Fan Diameter	m	1.27
Dry Weight	kg	2,192
Turbomachinery Arrangement	~	1-10-2-3
SFC @ beginning of cruise	lbm/hr/lbf	0.648
Max Diameter (A)	m	1.72
Max Length (B)	m	5.15

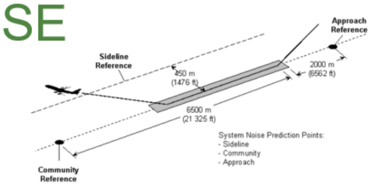


Description	Sea Level Static	Max Climb	Cruise
Net Thrust (kN)	75.7	11.4	8.3
OPR	26.15	30.77	24.58
FPR	1.65	1.74	1.61
BPR	4.35	4.36	4.83



C.2.5 Top Level Metrics

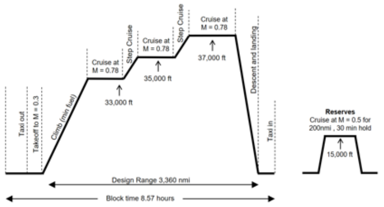
NOISE



	M&S Group	G-VI Cert.*
Lateral (EPNdB)	--	89.6
Flyover (EPNdB)	--	78.7
Approach (EPNdB)	--	88.3
Cumulative (EPNdB)	--	256.6
Margin to Chapter 14	--	9.5

*Noise Levels From: ICAO Noise Data Base ID: AIRBUS_22803

FUEL BURN



Trip Fuel 45,203 lbs
(20,504 kg)

	M&S Group
BizJet Technology Reference Aircraft Trip Fuel	20,504 kg
BizJet Technology Reference Aircraft MTOM	46,992 kg
BizJet TRA CO2 Metric (1/SAR/(RGF^0.24))	0.5984 kg/km
BizJet Fuel Burn per Available-Ton-Kilometer (R1 Range)	0.3356 kg/ATK

EMISSION

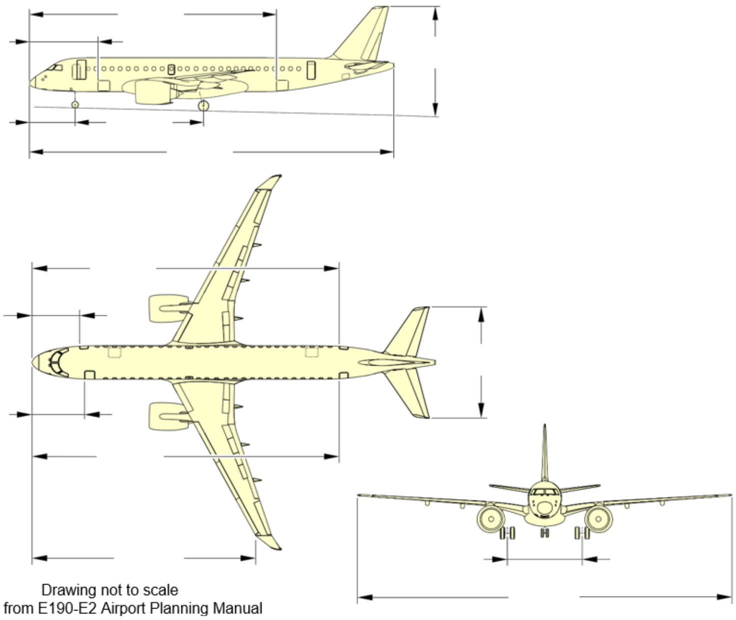
	M&S Group	ICAO Databank
Characteristic NOx dP/F00 (g/kN)	33.98	39.3
Characteristic NOx % Margin to CAEP/8 Limit	36.00	21.7

C.3 REGIONAL JET TRA

C.3.1 Assumptions

RJ Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

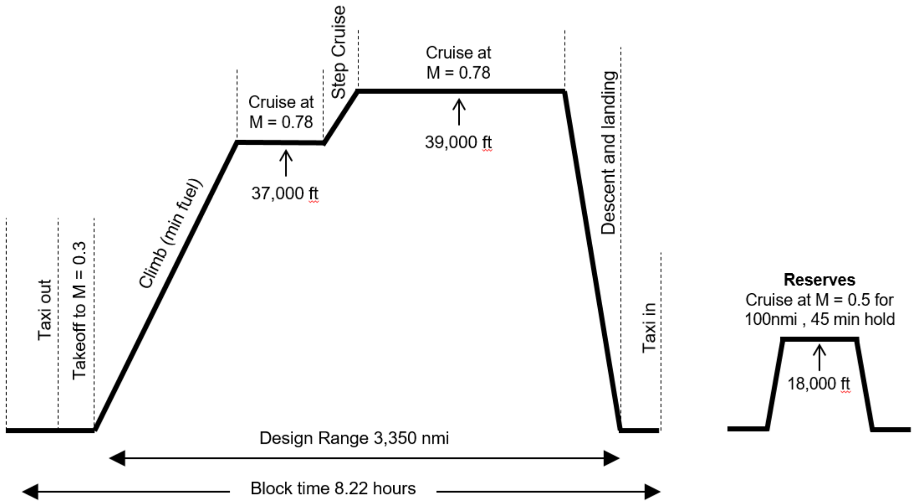
- Notional Embraer E190-E2
- Assumed payload of 21,120 lbm (9,579 kg)
    - 96 passengers @ 220 lbm each (@ design range including baggage)
- Design range of 3,350 nm
- Metallic main components (wing, fuselage, empennage)
- 2 geared fan engines (notional PW1922G) at high bypass ratio of ~11 (SLS)
    - Updated with respect to model used during IEIR work, since TCDS and ICAO Databank entry now exist
    - IEIR had used a notional PW1524G, since this one and the PW1922G have exact same turbomachinery arrangement, thrust class, and bypass ratio



Drawing not to scale
Taken from E190-E2 Airport Planning Manual

Description	Value
MTOW	124,341 lbs / 56,400 kg
Span	110.6 ft / 33.72 m
Wing Area	1108.6 ft^2 / 103.0 m^2
Aspect Ratio	11.03
¼ Chord Sweep	26.4 deg
HT Area	250.24 ft^2 / 23.25 m^2
HT Span	32.26 ft / 9.83 m
HT Aspect Ratio	4.16
HT ¼ Chord Sweep	29.95 deg
VT Area	174.29 ft^2 / 16.19 m^2
VT Span	17.26 ft / 5.26 m
VT Aspect Ratio	1.71
VT ¼ Chord Sweep	34.7 deg
Fuselage Length	118.2 ft / 36.0 m
Fuselage Height	11.0 ft / 3.3 m
Fuselage Width	9.9 ft / 3.0 m

C.3.2 Mission Profile



C.3.3 Vehicle Performance

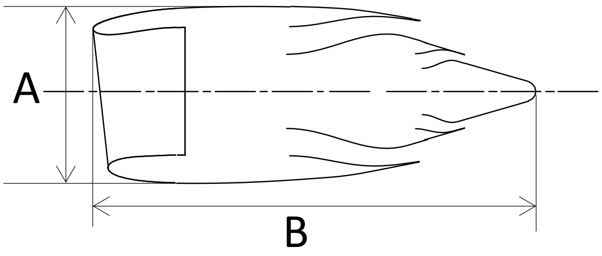
Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	71.5
Aspect ratio	AR	~	11.03
Bypass ratio (SLS)	BPR	~	11.16
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.84
C_{Lmax} Take-off	C_{LmaxTO}	~	1.92
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.78
Design fuel	~	kg	12,253
Design Payload at R_2		kg	21,120
Design Range at R_2	R2	nm	3,350
Fuselage height	DF	m	3.3
Fuselage length	XL	m	36.0
Fuselage width	WF	m	3.0
Initial Cruise Altitude	~	ft	37,000
Landing field length	LdgFL	m	1,860
Manufacturer's empty weight	MEW	kg	28,186
Maximum L/D at cruise	~	~	18.2
Maximum landing mass	MLM	kg	49,046
Maximum SLS thrust per engine	F_n	kN	105.9
Maximum take-off mass	MTOM	kg	56,400
Number of passengers	# pax		96
Operating empty weight	OEW	kg	33,000
Overall pressure ratio (SLS)	OPR	~	37.74
Ramp gross weight	~	kg	56,600
Reference geometric factor	RGF	m^2	77.5
Service ceiling	~	ft	41,000
Take-off field length	TOFL	m	1,674
Wing area	SW	m^2	103.0
Wing span	~	m	33.72
Wing sweep	~	degrees	26.4

Mass and Balance Summary: Empty Weight Breakout	**lbs**	**kg**
WING	12684	5753
HORIZONTAL	1303	591
VERTICAL TAIL	683	310
FUSELAGE	12288	5574
LANDING GEAR	4640	2105
NACELLE	1561	708
STRUCTURE TOTAL	33158	15040
ENGINES	11680	5298
FUEL SYSTEMS/ PLUMBING	521	236
PROPULSION TOTAL	12201	5534
SURFACE CONTROLS	1426	647
AUXILIARY POWER	778	353
ELECTRICAL & INSTRUMENTS	1701	772
HYDRAULICS	826	375
AVIONICS	1207	547
FURNISHINGS & MISC SYSTEMS	9681	4391
AIR CONDITIONING & ANTI-ICING	1160	526
FIXED EQUIPMENT TOTAL	16779	7611

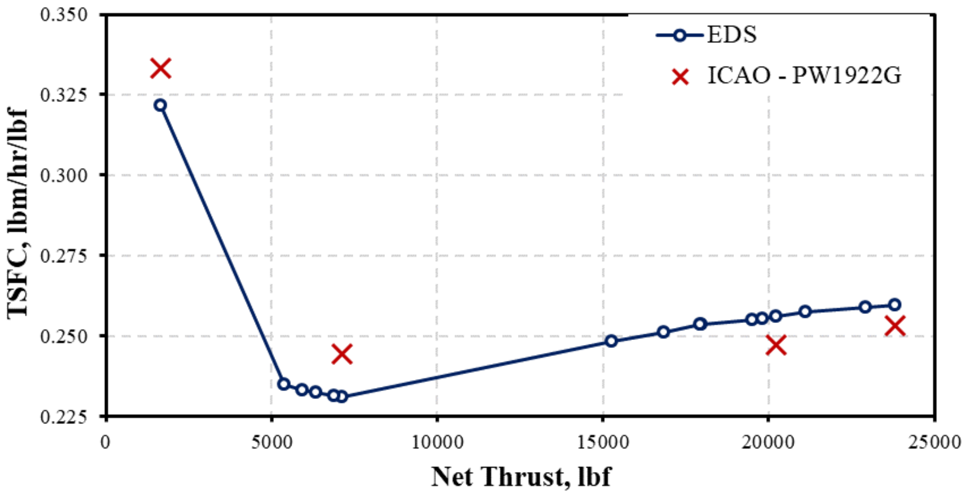
Mass and Balance Summary	**lbs**	**kg**
WEIGHT EMPTY	62139	28186
OPERATOR ITEMS	10613	4814
OPERATING WEIGHT EMPTY (OWE)	72752	33000
PAYLOAD 96 Passengers + baggage (220 lbs each)	21120	9580
ZERO FUEL WEIGHT	93872	42580
TOTAL FUEL	30909	14020
TRIP FUEL (TOTAL w/o RESERVES AND TAXI)	26578	12056
RAMP GROSS WEIGHT	124781	56600
Taxi Out Fuel Weight	440	200
MAXIMUM TAKE-OFF WEIGHT	124341	56400
OEW/MTOW	0.585	0.585

C.3.4 Engine Performance

Description	**Units**	**Value**
SLS Thrust	kN	105.9
Fan Diameter	m	1.85
Dry Weight	kg	2,430
Turbomachinery Arrangement	~	1-G-3-8-2-3
SFC @ beginning of cruise	lbm/hr/lbf	0.554
Max Diameter (A)	m	2.22
Max Length (B)	m	3.50

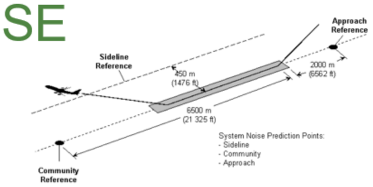


Description	**Sea Level Static**	**Max Climb**	**Cruise**
Net Thrust	105.9	21.7	20.2
OPR	37.74	45.84	43.32
FPR	1.44	1.51	1.48
BPR	11.16	11.17	11.51



C.3.5 Top Level Metrics

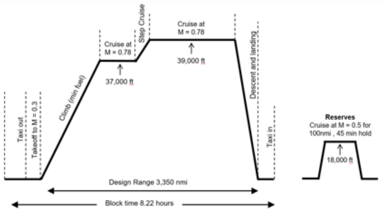
NOISE



	M&S Group	E190-E2 Cert.*
Lateral (EPNdB)	86.5	86.6
Flyover (EPNdB)	77.3	77.3
Approach (EPNdB)	91.4	91.4
Cumulative (EPNdB)	255.2	255.3
Margin to Chapter 14	13.0	13.0

*Noise Levels From: EASA Noise Data Base ID: A19221

FUEL BURN



Trip Fuel 27,007 lbs
(12,253 kg)

	M&S Group
RJ Technology Reference Aircraft Trip Fuel	12,250 kg
RJ Technology Reference Aircraft MTOM	56,400 kg
RJ TRA CO2 Metric (1/SAR/(RGF^0.24))	0.629 kg/km
RJ Fuel Burn per Available-Ton-Kilometer (R1 Range)	0.138 kg/ATK

EMISSION

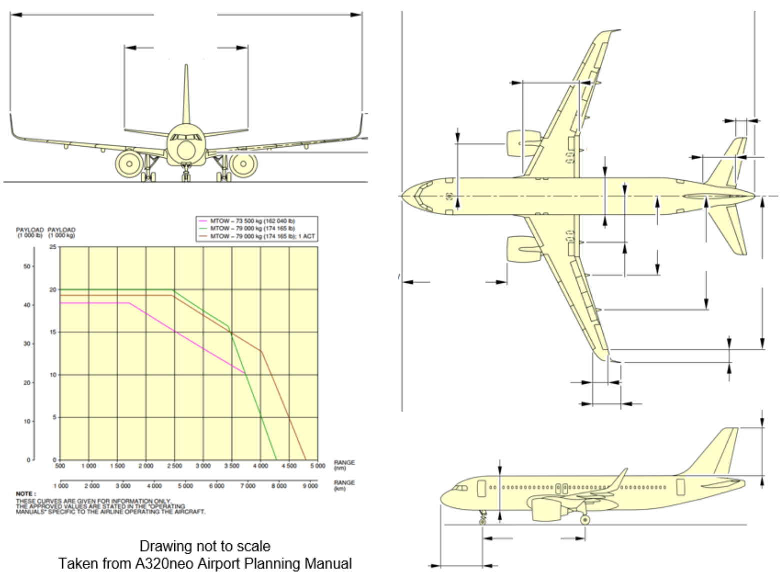
	M&S Group	ICAO Databank
Characteristic NOx dP/F00 (g/kN)	39.5	38.8 – 43.6
Characteristic NOx % Margin to CAEP/8 Limit	43.2	35.4 – 42.5

C.4 NARROW BODY TRA

C.4.1 Assumptions

NB Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

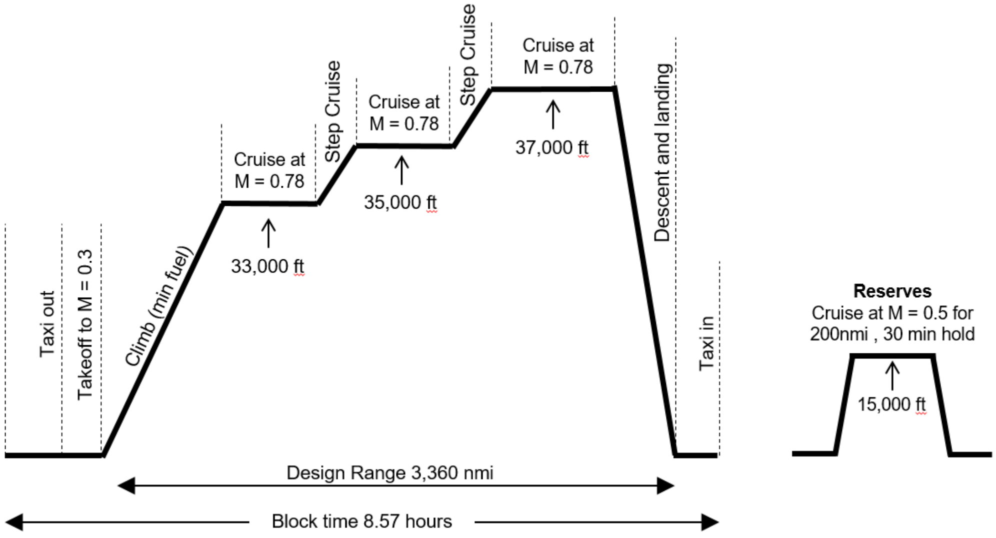
- **Notional** Airbus A320neo
- Assumed payload of 33,750 lbm (15,307 kg)
    - 150 pax @ 225 lbm each (@ design range including baggage)
- Design range of 3,360 nm
- Metallic main components (wing, fuselage, empennage)
- 2 geared fan engines (**notional** PW1133G) at high bypass ratio of ~11 (SLS)
    - Created PW1133G model from publically available information and ICAO databank
    - De-rated PW1133G to PW1127G performance to match ICAO powerhook



Drawing not to scale
Taken from A320neo Airport Planning Manual

Description	Value
MTOW	174,165 lbs / 79,000 kg
Span	106.3 ft / 32.3 m
Wing Area	1130.5 ft^2 / 105.0 m^2
Aspect Ratio	9.1
¼ Chord Sweep	24.9 deg
HT Area	331.1 ft^2 / 30.8 m^2
HT Span	41.0 ft / 12.5 m
HT Aspect Ratio	5.08
HT ¼ Chord Sweep	27.4 deg
VT Area	218.1 ft^2 / 20.3 m^2
VT Span	18.6 ft / 5.7 m
VT Aspect Ratio	1.59
VT ¼ Chord Sweep	35.0 deg
Fuselage Length	123.3 ft / 37.6 m
Fuselage Height	13.6 ft / 4.1 m
Fuselage Width	12.8 ft / 3.9 m

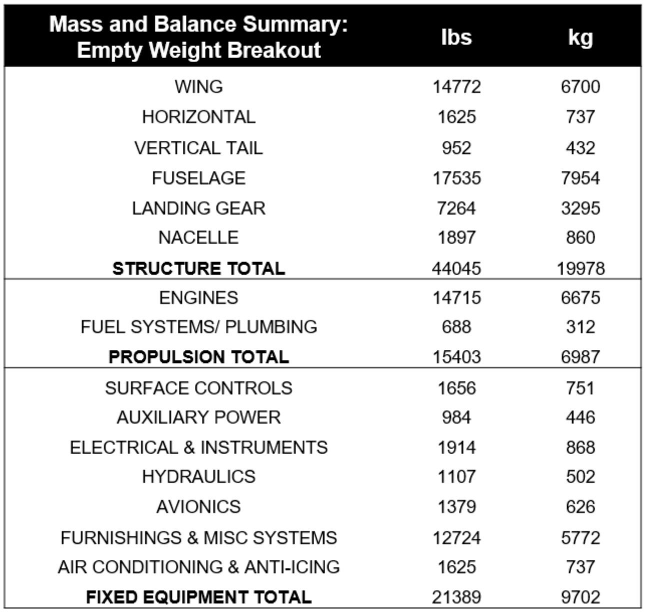
C.4.2 Mission Profile



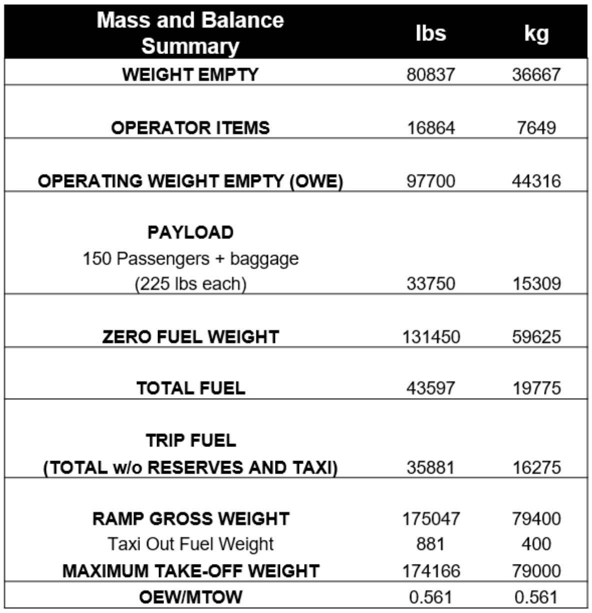
C.4.3 Vehicle Performance

Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	70.5
Aspect ratio	AR	~	9.1
Bypass ratio (SLS)	BPR	~	12.07
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.98
C_{Lmax} Take-off	C_{LmaxTO}	~	1.85
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.78
Design fuel	~	kg	16.985
Design Payload at R_2		kg	15,309
Design Range at R_2	R2	nm	3,360
Fuselage height	DF	m	4.1
Fuselage length	XL	m	37.6
Fuselage width	WF	m	3.9
Initial Cruise Altitude	~	ft	33,000
Landing field length	LdgFL	m	1,960
Manufacturer's empty weight	MEW	kg	36,667
Maximum L/D at cruise	~	~	17.2
Maximum landing mass	MLM	kg	67,394
Maximum SLS thrust per engine	F_n	kN	120.4
Maximum take-off mass	MTOM	kg	79,000
Number of passengers	# pax		150
Operating empty weight	OEW	kg	44,316
Overall pressure ratio (SLS)	OPR	~	32.12
Ramp gross weight	~	kg	79,400
Reference geometric factor	RGF	m^2	108.93
Service ceiling	~	ft	39,000
Take-off field length	TOFL	m	2,400
Wing area	SW	m^2	105.0
Wing span	~	m	32.3

Wing ¼ chord sweep	~	degrees	24.9



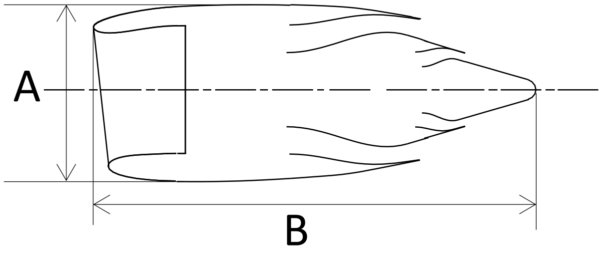
Mass and Balance Summary: Empty Weight Breakout	lbs	kg
WING	14772	6700
HORIZONTAL	1625	737
VERTICAL TAIL	952	432
FUSELAGE	17535	7954
LANDING GEAR	7264	3295
NACELLE	1897	860
STRUCTURE TOTAL	44045	19978
ENGINES	14715	6675
FUEL SYSTEMS/ PLUMBING	688	312
PROPULSION TOTAL	15403	6987
SURFACE CONTROLS	1656	751
AUXILIARY POWER	984	446
ELECTRICAL & INSTRUMENTS	1914	868
HYDRAULICS	1107	502
AVIONICS	1379	626
FURNISHINGS & MISC SYSTEMS	12724	5772
AIR CONDITIONING & ANTI-ICING	1625	737
FIXED EQUIPMENT TOTAL	21389	9702



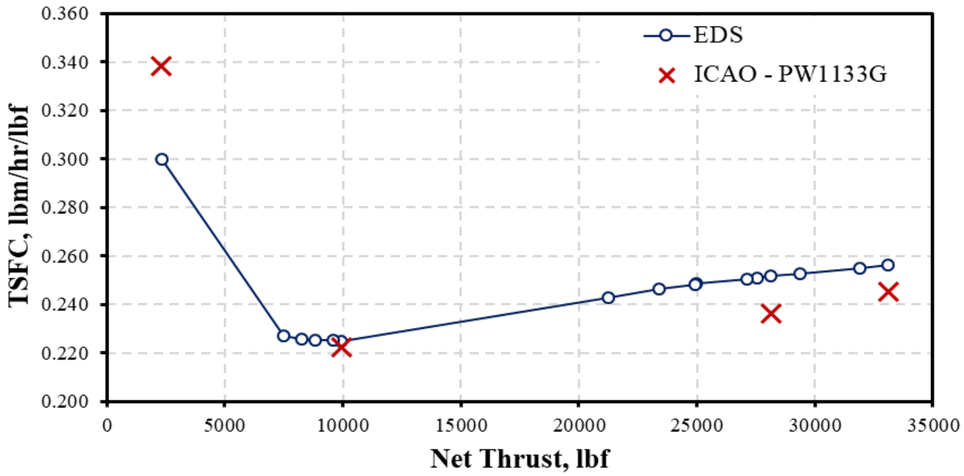
Mass and Balance Summary	lbs	kg
WEIGHT EMPTY	80837	36667
OPERATOR ITEMS	16864	7649
OPERATING WEIGHT EMPTY (OWE)	97700	44316
PAYLOAD 150 Passengers + baggage (225 lbs each)	33750	15309
ZERO FUEL WEIGHT	131450	59625
TOTAL FUEL	43597	19775
TRIP FUEL **(TOTAL w/o RESERVES AND TAXI)**	35881	16275
RAMP GROSS WEIGHT	175047	79400
Taxi Out Fuel Weight	881	400
MAXIMUM TAKE-OFF WEIGHT	174166	79000
OEW/MTOW	0.561	0.561

C.4.4 Engine Performance

Description	Units	Value
SLS Thrust	kN	120.4
Fan Diameter	m	2.06
Dry Weight	kg	2,250
Turbomachinery Arrangement	~	1-G-3-8-2-3
SFC @ beginning of cruise	lbm/hr/lbf	0.534
Max Diameter (A)	m	2.55
Max Length (B)	m	3.51

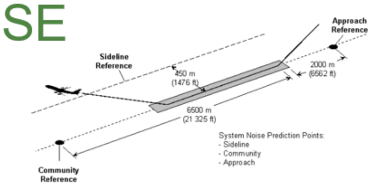


Description	Sea Level Static	Max Climb	Cruise
Net Thrust	120.4	31.3	27.2
OPR	32.12	47.61	41.95
FPR	1.38	1.54	1.49
BPR	12.07	11.29	12.14



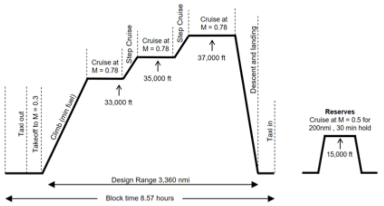
C.4.5 Top Level Metrics

NOISE



	M&S Group	A320neo Cert.*
Lateral (EPNdB)	--	86.8
Flyover (EPNdB)	--	82.0
Approach (EPNdB)	--	92.2
Cumulative (EPNdB)	--	261.0
Margin to Chapter 14	--	11.6

*Noise Levels From: ICAO Noise Data Base ID: AIRBUS_22803



FUEL BURN

Trip Fuel 37,445 lbs
(16,985 kg)

	M&S Group
NB Technology Reference Aircraft Trip Fuel	16,985 kg
NB Technology Reference Aircraft MTOM	79,200 kg
NB TRA CO2 Metric (1/SAR/(RGF^0.24))	0.810 kg/km
NB Fuel Burn per Available-Ton-Kilometer (R1 Range)	0.133 kg/ATK

EMISSION

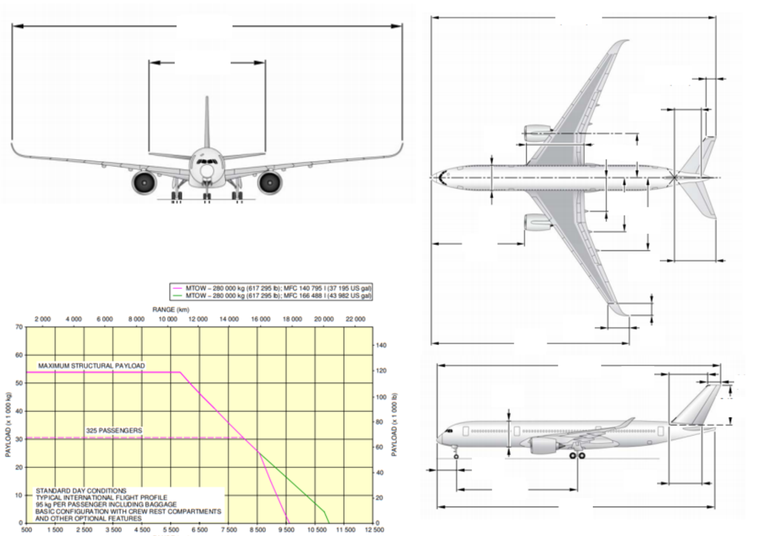
	M&S Group	ICAO Databank
Characteristic NOx dP/F00 (g/kN)	31.4	33.62
Characteristic NOx % Margin to CAEP/8 Limit	45.51	42.6 – 48.9

C.5 WIDE BODY TRA

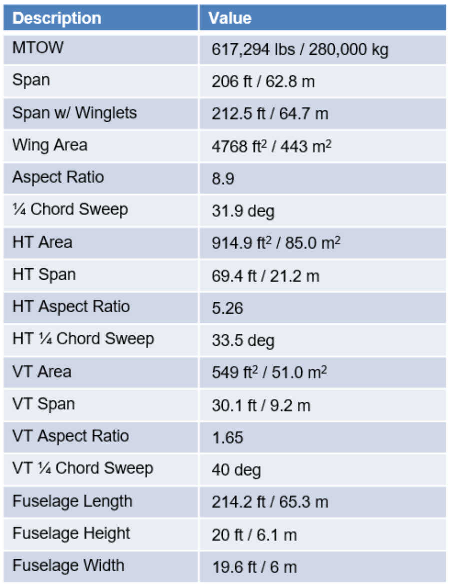
C.5.1 Assumptions

WB Technology Reference Aircraft (TRA) is based on a technology level in line with state-of-the-art of the vehicles in production today:

- **Notional** Airbus A350-900
- Assumed payload of 68,250 bm (30,958 kg)
    - 325 pax @ 210 lbm each (@ design range including baggage)
- Design range of 8,000 nm
- Composite main components (wing, fuselage, empennage)
- 2 three-spool engines (**notional** Rolls Royce Trent XWB-84) at high bypass ratio of ~9 (SLS)
    - Created RR Trent XWB-84 model from publically available information and ICAO databank

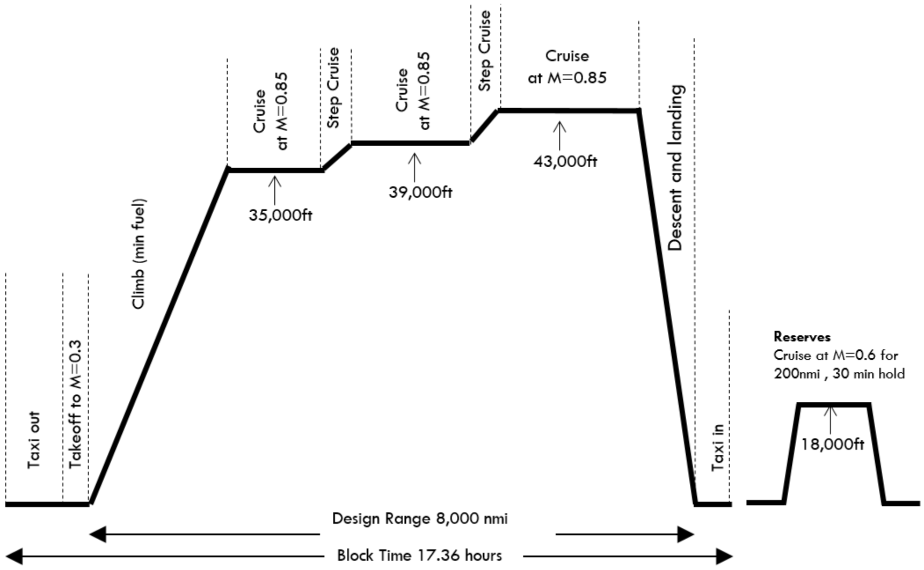


*Drawings not to scale
Taken from A350 Airport Planning Manual



Description	Value
MTOW	617,294 lbs / 280,000 kg
Span	206 ft / 62.8 m
Span w/ Winglets	212.5 ft / 64.7 m
Wing Area	4768 ft^2 / 443 m^2
Aspect Ratio	8.9
¼ Chord Sweep	31.9 deg
HT Area	914.9 ft^2 / 85.0 m^2
HT Span	69.4 ft / 21.2 m
HT Aspect Ratio	5.26
HT ¼ Chord Sweep	33.5 deg
VT Area	549 ft^2 / 51.0 m^2
VT Span	30.1 ft / 9.2 m
VT Aspect Ratio	1.65
VT ¼ Chord Sweep	40 deg
Fuselage Length	214.2 ft / 65.3 m
Fuselage Height	20 ft / 6.1 m
Fuselage Width	19.6 ft / 6 m

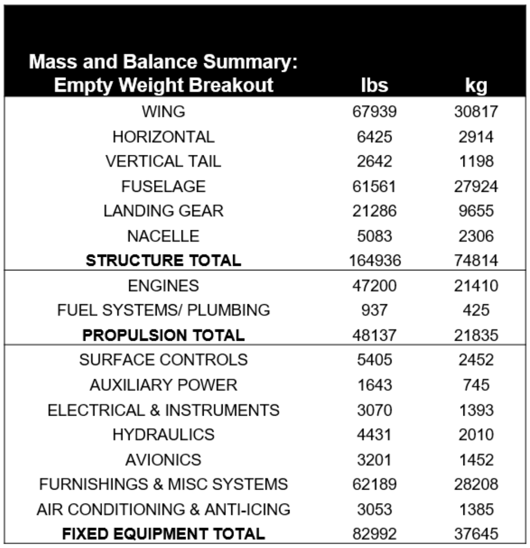
C.5.2 Mission Profile



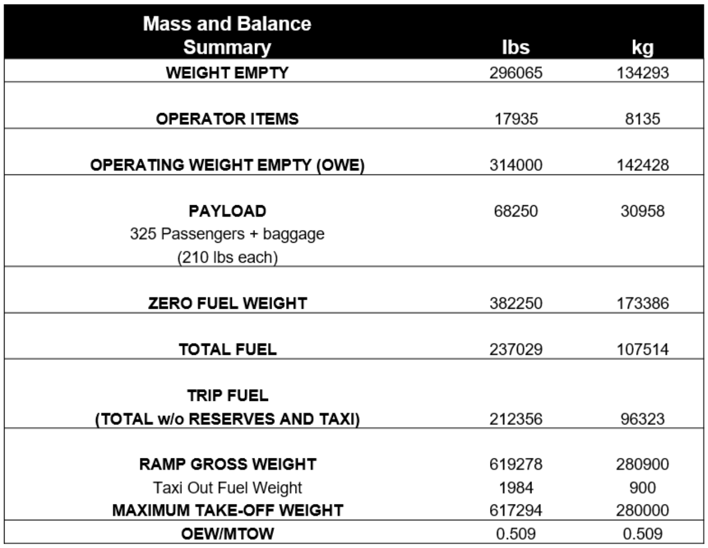
C.5.3 Vehicle Performance

Parameter	Acronym	Units	Value
Approach Speed	V_{app}	mps	71.5
Aspect ratio	AR	~	8.9
Bypass ratio (SLS)	BPR	~	9.01
C_{Lmax} Landing	$C_{LmaxLdg}$	~	2.47
C_{Lmax} Take-off	C_{LmaxTO}	~	2.11
Cockpit crew	~	~	2
Design cruise speed	M_{des}		0.85
Design fuel	~	kg	100,972
Design Payload at R_2		kg	30,958
Design Range at R_2	R2	nm	8,000
Fuselage height	DF	m	6.1
Fuselage length	XL	m	65.3
Fuselage width	WF	m	6.0
Initial Cruise Altitude	~	ft	35,000
Landing field length	LdgFL	m	2,000
Manufacturer's empty weight	MEW	kg	134,293
Maximum L/D at cruise	~	~	20.3
Maximum landing mass	MLM	kg	206,983
Maximum SLS thrust per engine	F_n	kN	379
Maximum take-off mass	MTOM	kg	280,000
Number of passengers	# pax		325
Operating empty weight	OEW	kg	142,428
Overall pressure ratio (SLS)	OPR	~	41.11
Ramp gross weight	~	kg	280,900
Reference geometric factor	RGF	m^2	299
Service ceiling	~	ft	43,000
Take-off field length	TOFL	m	2,480
Wing area	SW	m^2	443

Wing span	~	m	62.8
Wing ¼ chord sweep	~	degrees	31.9



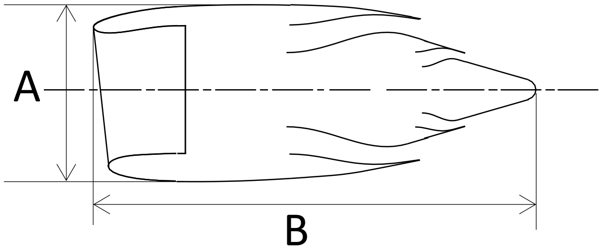
Mass and Balance Summary: Empty Weight Breakout	lbs	kg
WING	67939	30817
HORIZONTAL	6425	2914
VERTICAL TAIL	2642	1198
FUSELAGE	61561	27924
LANDING GEAR	21286	9655
NACELLE	5083	2306
STRUCTURE TOTAL	164936	74814
ENGINES	47200	21410
FUEL SYSTEMS/ PLUMBING	937	425
PROPULSION TOTAL	48137	21835
SURFACE CONTROLS	5405	2452
AUXILIARY POWER	1643	745
ELECTRICAL & INSTRUMENTS	3070	1393
HYDRAULICS	4431	2010
AVIONICS	3201	1452
FURNISHINGS & MISC SYSTEMS	62189	28208
AIR CONDITIONING & ANTI-ICING	3053	1385
FIXED EQUIPMENT TOTAL	82992	37645



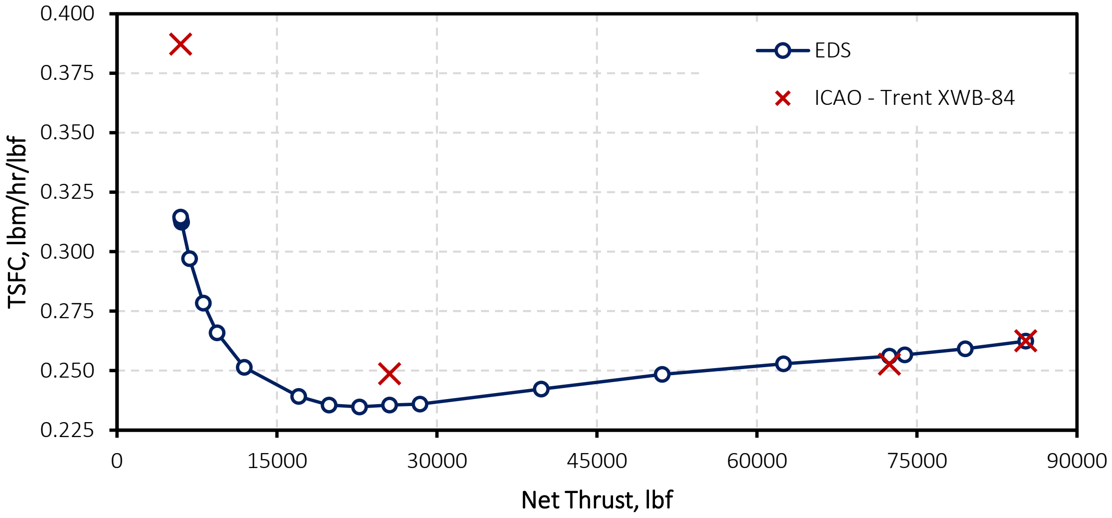
Mass and Balance Summary	lbs	kg
WEIGHT EMPTY	296065	134293
OPERATOR ITEMS	17935	8135
OPERATING WEIGHT EMPTY (OWE)	314000	142428
PAYLOAD 325 Passengers + baggage (210 lbs each)	68250	30958
ZERO FUEL WEIGHT	382250	173386
TOTAL FUEL	237029	107514
TRIP FUEL **(TOTAL w/o RESERVES AND TAXI)**	212356	96323
RAMP GROSS WEIGHT	619278	280900
Taxi Out Fuel Weight	1984	900
MAXIMUM TAKE-OFF WEIGHT	617294	280000
OEW/MTOW	0.509	0.509

C.5.4 Engine Performance

Description	Units	Value
SLS Thrust	kN	379
Fan Diameter	m	3.0
Dry Weight	kg	8,885
Turbomachinery Arrangement	~	1-8-6-1-2-6
SFC @ beginning of cruise	lbm/hr/lbf	0.522
Max Diameter (A)	m	3.63
Max Length (B)	m	6.74

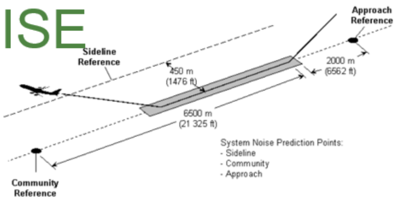


Description	Sea Level Static	Max Climb	Cruise
Net Thrust	379	64.9	56.3
OPR	41.11	46.75	42.14
FPR	1.57	1.64	1.58
BPR	9.01	9.14	9.52



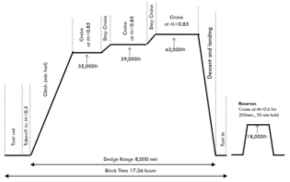
C.5.5 Top Level Metrics

NOISE



	M&S Group	A350-900 Cert.
Lateral (EPNdB)	91.5	91.5
Flyover (EPNdB)	85.7	85.9
Approach (EPNdB)	96.5	96.5
Cumulative (EPNdB)	273.7	273.9
Margin to Chapter 14	15.1	14.8

*Noise Levels From:
ICAO Certification
Database
ID: AIRBUS_22758



FUEL BURN

Trip Fuel 222,605 lbs
(100,972 kg)

	M&S Group
WB Technology Reference Aircraft Trip Fuel	100,972 kg
WB Technology Reference Aircraft MTOM	280,000 kg
WB TRA CO2 Metric (1/SAR/(RGF^0.24))	1.68 kg/km
WB Fuel Burn per Available-Ton-Kilometer (R1 Range)	0.125 kg/ATK

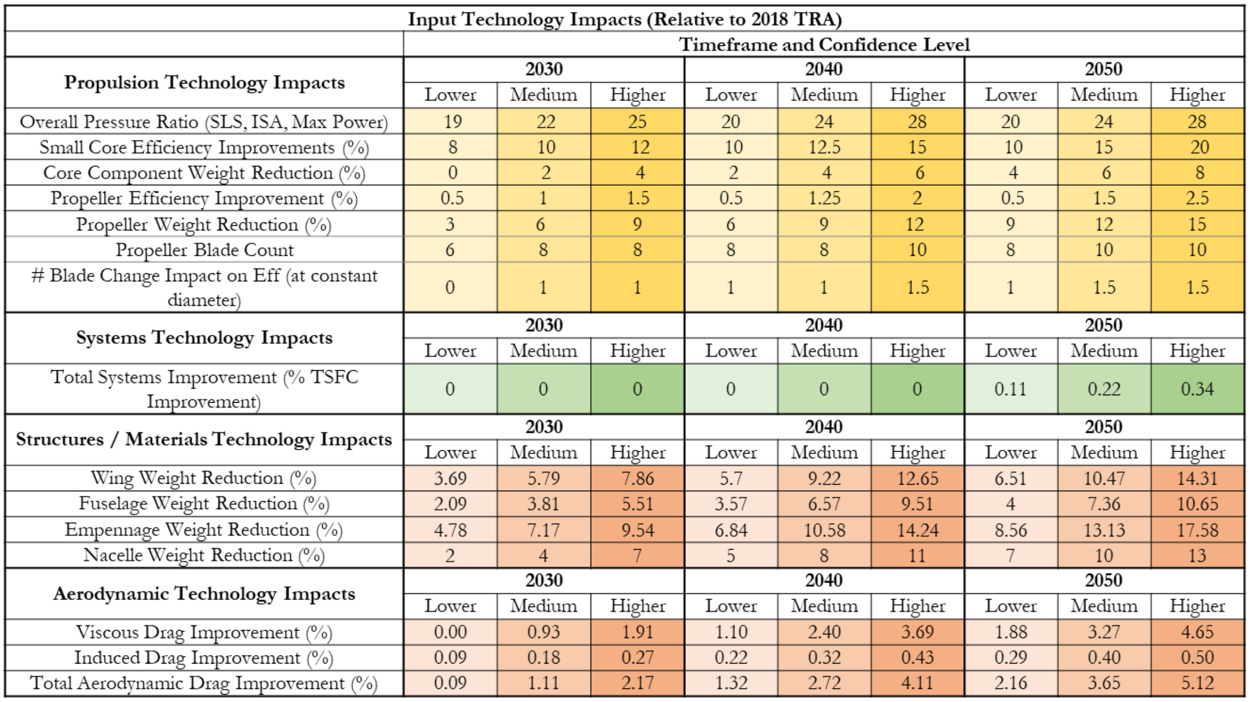
EMISSION

	M&S Group	ICAO Database
Characteristic NOx dP/F00 (g/kN)	55.68	55.1 – 61.9
Characteristic NOx % Margin to CAEP/8 Limit	28.6%	14.1% – 23.8%

ANNEX D. TRA TECHNOLOGY IMPACTS

This appendix provides the resulting 2030, 2040, and 2050 technology impacts obtained from the Technology ad hoc groups for each of the TRAs. Note that MCL = Maximum Climb Condition and MCR = Maximum Cruise Condition

D.1 TURBOPROP TECHNOLOGY IMPACTS



Input Technology Impacts (Relative to 2018 TRA)									
	Timeframe and Confidence Level								
Propulsion Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Overall Pressure Ratio (SLS, ISA, Max Power)	19	22	25	20	24	28	20	24	28
Small Core Efficiency Improvements (%)	8	10	12	10	12.5	15	10	15	20
Core Component Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Propeller Efficiency Improvement (%)	0.5	1	1.5	0.5	1.25	2	0.5	1.5	2.5
Propeller Weight Reduction (%)	3	6	9	6	9	12	9	12	15
Propeller Blade Count	6	8	8	8	8	10	8	10	10
# Blade Change Impact on Eff (at constant diameter)	0	1	1	1	1	1.5	1	1.5	1.5
Systems Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Total Systems Improvement (% TSFC Improvement)	0	0	0	0	0	0	0.11	0.22	0.34
Structures / Materials Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Wing Weight Reduction (%)	3.69	5.79	7.86	5.7	9.22	12.65	6.51	10.47	14.31
Fuselage Weight Reduction (%)	2.09	3.81	5.51	3.57	6.57	9.51	4	7.36	10.65
Empennage Weight Reduction (%)	4.78	7.17	9.54	6.84	10.58	14.24	8.56	13.13	17.58
Nacelle Weight Reduction (%)	2	4	7	5	8	11	7	10	13
Aerodynamic Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Viscous Drag Improvement (%)	0.00	0.93	1.91	1.10	2.40	3.69	1.88	3.27	4.65
Induced Drag Improvement (%)	0.09	0.18	0.27	0.22	0.32	0.43	0.29	0.40	0.50
Total Aerodynamic Drag Improvement (%)	0.09	1.11	2.17	1.32	2.72	4.11	2.16	3.65	5.12

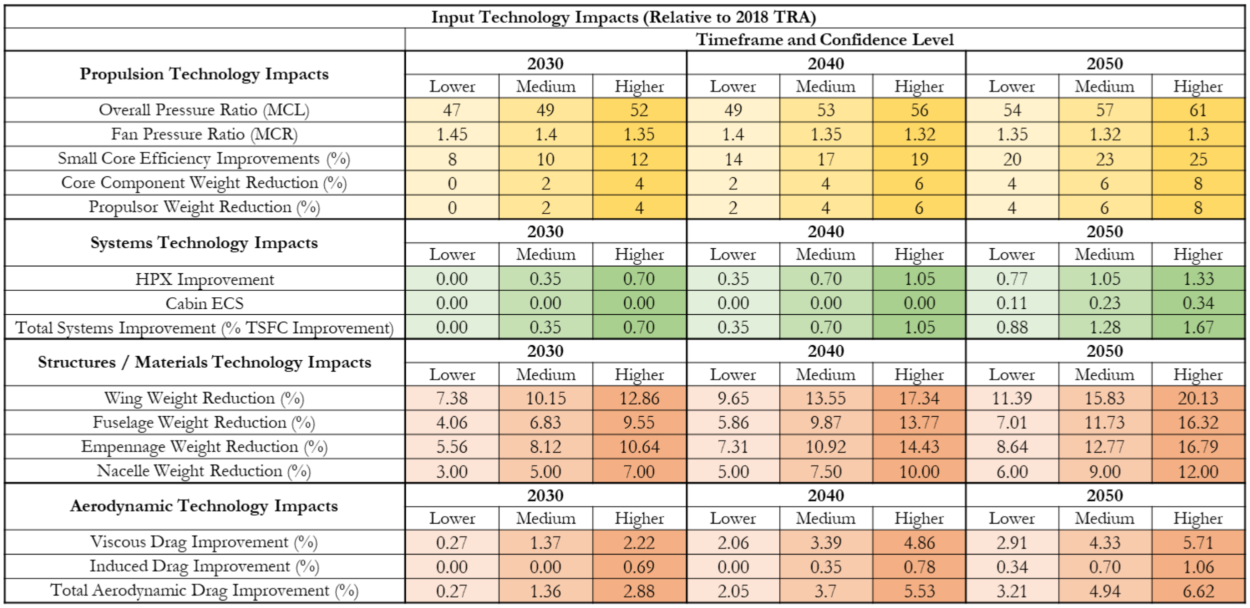
D.2 BUSINESS JET TECHNOLOGY IMPACTS

Input Technology Impacts (Relative to 2018 TRA)									
	Timeframe and Confidence Level								
Propulsion Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Overall Pressure Ratio (MCL)	29	30	31	32	33	34	38	40	42
Fan Pressure Ratio (MCR)	1.68	1.67	1.65	1.64	1.63	1.62	1.62	1.6	1.58
Small Core Efficiency Improvements (%)	8	10	12	12	12	12	13	14	15
Core Component Weight Reduction (%)	0	2	3	2	3	4	4	5	6
Propulsor Weight Reduction (%)	0	2	3	2	3	4	4	5	6
Systems Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
HPX Improvement	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cabin ECS	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.23	0.34
Total Systems Improvement (% TSFC Improvement)	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.23	0.34
Structures / Materials Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Wing Weight Reduction (%)	2.99	4.95	6.88	4.70	7.97	11.16	5.23	8.83	12.33
Fuselage Weight Reduction (%)	0.80	2.53	4.24	1.39	4.44	7.42	1.66	5.25	8.76
Empennage Weight Reduction (%)	1.35	3.28	5.18	1.90	4.93	7.91	2.18	5.72	9.18
Nacelle Weight Reduction (%)	2.00	3.00	4.00	4.00	5.00	6.00	5.50	6.50	7.50
Aerodynamic Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Viscous Drag Improvement (%)	0.12	0.87	1.53	1.09	1.92	2.91	1.36	2.42	3.67
Induced Drag Improvement (%)	0.00	0.00	0.46	0.00	0.33	0.73	0.10	0.40	0.76
Total Aerodynamic Drag Improvement (%)	0.12	0.87	1.98	1.08	2.23	3.60	1.45	2.79	4.36

D.3 REGIONAL JET TECHNOLOGY IMPACTS

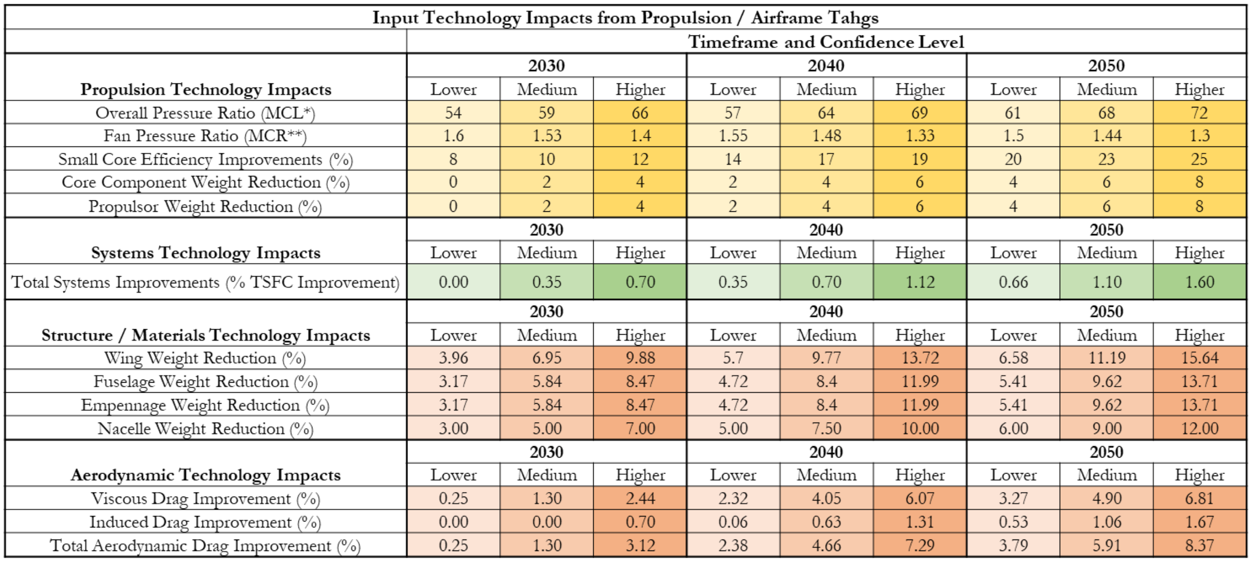
Input Technology Impacts (Relative to 2018 TRA)									
	Timeframe and Confidence Level								
Propulsion Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Overall Pressure Ratio (MCL)	46	48	50	46	50	53	48	53	57
Fan Pressure Ratio (MCR)	1.48	1.43	1.4	1.43	1.4	1.37	1.4	1.37	1.34
Small Core Efficiency Improvements (%)	8	10	12	14	17	19	20	23	25
Core Component Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Propulsor Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Systems Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
HPX Improvement	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cabin ECS	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.23	0.34
Total Systems Improvement (% TSFC Improvement)	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.23	0.34
Structures / Materials Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Wing Weight Reduction (%)	3.69	5.79	7.86	5.70	9.22	12.65	6.51	10.47	14.31
Fuselage Weight Reduction (%)	2.09	3.81	5.51	3.57	6.57	9.51	4.00	7.36	10.65
Empennage Weight Reduction (%)	4.03	5.94	7.82	5.66	8.63	11.55	6.76	10.39	13.93
Nacelle Weight Reduction (%)	2.00	3.00	4.00	4.00	5.00	6.00	5.50	6.50	7.50
Aerodynamic Technology Impacts	**2030**			**2040**			**2050**		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Viscous Drag Improvement (%)	0.29	1.54	2.41	1.49	2.44	3.54	1.98	3.12	4.46
Induced Drag Improvement (%)	0.00	0.00	0.69	0.00	0.33	0.73	0.10	0.40	0.76
Total Aerodynamic Drag Improvement (%)	0.29	1.54	3.06	1.48	2.74	4.20	2.07	3.48	5.12

D.4 NARROW BODY TECHNOLOGY IMPACTS



Input Technology Impacts (Relative to 2018 TRA)									
	Timeframe and Confidence Level								
Propulsion Technology Impacts	2030			2040			2050		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Overall Pressure Ratio (MCL)	47	49	52	49	53	56	54	57	61
Fan Pressure Ratio (MCR)	1.45	1.4	1.35	1.4	1.35	1.32	1.35	1.32	1.3
Small Core Efficiency Improvements (%)	8	10	12	14	17	19	20	23	25
Core Component Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Propulsor Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Systems Technology Impacts	2030			2040			2050		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
HPX Improvement	0.00	0.35	0.70	0.35	0.70	1.05	0.77	1.05	1.33
Cabin ECS	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.23	0.34
Total Systems Improvement (% TSFC Improvement)	0.00	0.35	0.70	0.35	0.70	1.05	0.88	1.28	1.67
Structures / Materials Technology Impacts	2030			2040			2050		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Wing Weight Reduction (%)	7.38	10.15	12.86	9.65	13.55	17.34	11.39	15.83	20.13
Fuselage Weight Reduction (%)	4.06	6.83	9.55	5.86	9.87	13.77	7.01	11.73	16.32
Empennage Weight Reduction (%)	5.56	8.12	10.64	7.31	10.92	14.43	8.64	12.77	16.79
Nacelle Weight Reduction (%)	3.00	5.00	7.00	5.00	7.50	10.00	6.00	9.00	12.00
Aerodynamic Technology Impacts	2030			2040			2050		
	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Viscous Drag Improvement (%)	0.27	1.37	2.22	2.06	3.39	4.86	2.91	4.33	5.71
Induced Drag Improvement (%)	0.00	0.00	0.69	0.00	0.35	0.78	0.34	0.70	1.06
Total Aerodynamic Drag Improvement (%)	0.27	1.36	2.88	2.05	3.7	5.53	3.21	4.94	6.62

D.5 WIDE BODY TECHNOLOGY IMPACTS



Input Technology Impacts from Propulsion / Airframe Tahgs									
	Timeframe and Confidence Level								
	2030			2040			2050		
Propulsion Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Overall Pressure Ratio (MCL*)	54	59	66	57	64	69	61	68	72
Fan Pressure Ratio (MCR**)	1.6	1.53	1.4	1.55	1.48	1.33	1.5	1.44	1.3
Small Core Efficiency Improvements (%)	8	10	12	14	17	19	20	23	25
Core Component Weight Reduction (%)	0	2	4	2	4	6	4	6	8
Propulsor Weight Reduction (%)	0	2	4	2	4	6	4	6	8
	2030			2040			2050		
Systems Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Total Systems Improvements (% TSFC Improvement)	0.00	0.35	0.70	0.35	0.70	1.12	0.66	1.10	1.60
	2030			2040			2050		
Structure / Materials Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Wing Weight Reduction (%)	3.96	6.95	9.88	5.7	9.77	13.72	6.58	11.19	15.64
Fuselage Weight Reduction (%)	3.17	5.84	8.47	4.72	8.4	11.99	5.41	9.62	13.71
Empennage Weight Reduction (%)	3.17	5.84	8.47	4.72	8.4	11.99	5.41	9.62	13.71
Nacelle Weight Reduction (%)	3.00	5.00	7.00	5.00	7.50	10.00	6.00	9.00	12.00
	2030			2040			2050		
Aerodynamic Technology Impacts	Lower	Medium	Higher	Lower	Medium	Higher	Lower	Medium	Higher
Viscous Drag Improvement (%)	0.25	1.30	2.44	2.32	4.05	6.07	3.27	4.90	6.81
Induced Drag Improvement (%)	0.00	0.00	0.70	0.06	0.63	1.31	0.53	1.06	1.67
Total Aerodynamic Drag Improvement (%)	0.25	1.30	3.12	2.38	4.66	7.29	3.79	5.91	8.37

ANNEX E. DESIGN VARIABLE RANGES AND CONSTRAINTS

E.1 TURBOPROP

Design Parameters and Ranges									
	Timeframe								
		2018		2030		2040		2050	
Design Parameter	TRA	Min	Max	Min	Max	Min	Max	Min	Max
Wing Loading [lb/ft2]	96.3	96.3	96.3	90	100	85	110	80	120
Aspect Ratio - Lower Progress	12.8			12	12.8	12	13	12	13.5
Aspect Ratio - Medium Progress		12	12.8	12	12.9	12	13.25	12	13.75
Aspect Ratio - Higher Progress				12	13	12	13.5	12	14
Power to Weight Ratio (hp/lb)	0.14	0.14	0.14	0.1285	0.155	0.1285	0.16	0.1285	0.165
T41 Delta from Baseline (SLS, ISA) [R]	Baseline	-10	10	-100	100	-100	150	-100	200

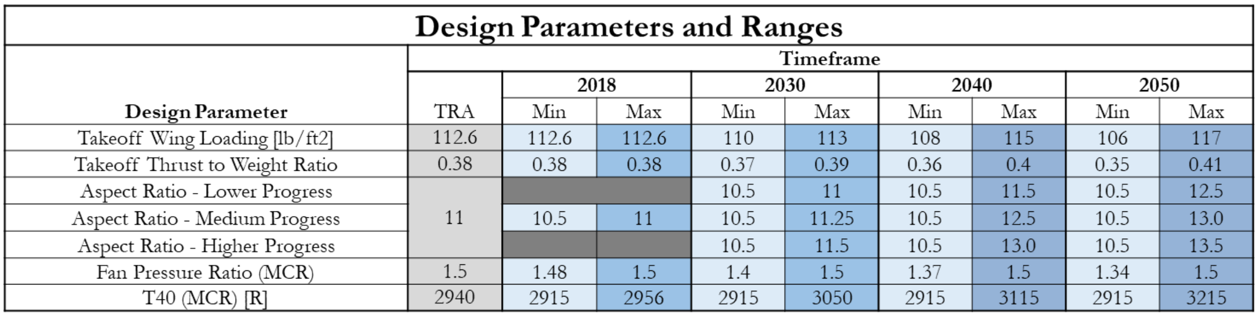
Constraints					
Constraint Parameter	**Timeframe**				
	2018 TRA	**2018 Opt**	**2030**	**2040**	**2050**
Takeoff Field Length [ft]	4630				
Gate Constraint [ft]	117				

E.2 BUSINESS JET

Design Parameters and Ranges									
Design Parameter	Timeframe								
	TRA	2018		2030		2040		2050	
		Min	Max	Min	Max	Min	Max	Min	Max
Takeoff Wing Loading [lb/ft^2]	81.1	81.1	81.1	80	82	78	84	76	86
Takeoff Thrust to Weight Ratio	0.327	0.327	0.327	0.32	0.34	0.31	0.35	0.3	0.36
Aspect Ratio - Lower Progress	7.7			7.5	8.25	7.5	8.5	7.5	8.5
Aspect Ratio - Medium Progress		7.5	8.25	7.5	8.5	7.5	8.75	7.5	9
Aspect Ratio - Higher Progress				7.5	8.75	7.5	9	7.5	9.5
Fan Pressure Ratio (MCR)	1.7	1.68	1.72	1.65	1.72	1.62	1.72	1.58	1.72
T40 (MCR) [R]	2577	2560	2610	2560	2695	2560	2760	2560	2860

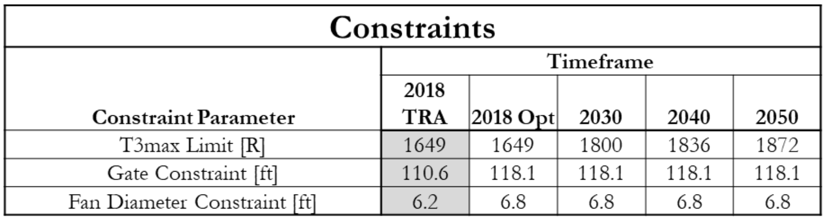
Constraints					
Constraint Parameter	**Timeframe**				
	2018 TRA	**2018 Opt**	**2030**	**2040**	**2050**
T3max Limit [R]	1505	1505	1620	1710	1800
Gate Constraint [ft]	N/A				
Fan Diameter Constraint [ft]	N/A				

E.3 REGIONAL JET



Design Parameters and Ranges

Design Parameter	Timeframe								
		2018		2030		2040		2050	
	TRA	Min	Max	Min	Max	Min	Max	Min	Max
Takeoff Wing Loading [lb/ft2]	112.6	112.6	112.6	110	113	108	115	106	117
Takeoff Thrust to Weight Ratio	0.38	0.38	0.38	0.37	0.39	0.36	0.4	0.35	0.41
Aspect Ratio - Lower Progress	11			10.5	11	10.5	11.5	10.5	12.5
Aspect Ratio - Medium Progress		10.5	11	10.5	11.25	10.5	12.5	10.5	13.0
Aspect Ratio - Higher Progress				10.5	11.5	10.5	13.0	10.5	13.5
Fan Pressure Ratio (MCR)	1.5	1.48	1.5	1.4	1.5	1.37	1.5	1.34	1.5
T40 (MCR) [R]	2940	2915	2956	2915	3050	2915	3115	2915	3215

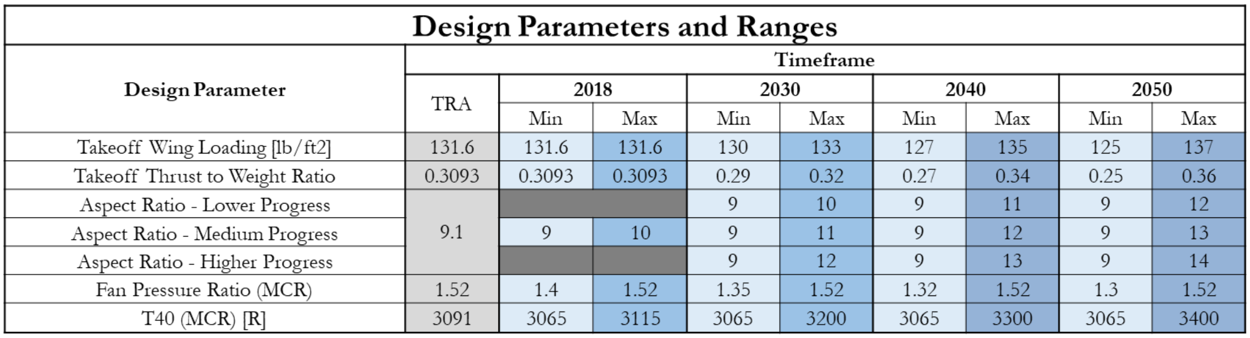


Constraints

Constraint Parameter	Timeframe				
	2018 TRA	2018 Opt	2030	2040	2050
T3max Limit [R]	1649	1649	1800	1836	1872
Gate Constraint [ft]	110.6	118.1	118.1	118.1	118.1
Fan Diameter Constraint [ft]	6.2	6.8	6.8	6.8	6.8

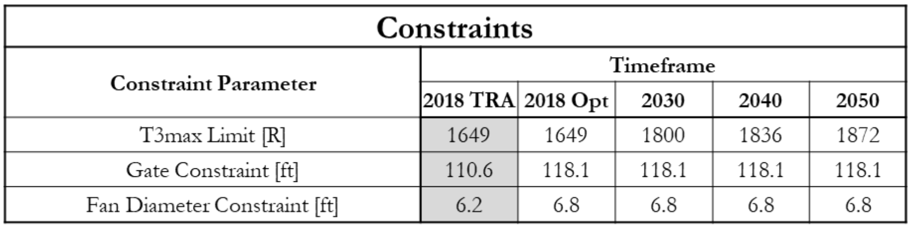
The fan diameter constraint was to ensure at least 2 feet of engine ground clearance. No optimal ATWs required a folding wing tip device.

E.4 NARROW BODY



Design Parameters and Ranges

Design Parameter	Timeframe								
	TRA	2018		2030		2040		2050	
		Min	Max	Min	Max	Min	Max	Min	Max
Takeoff Wing Loading [lb/ft2]	131.6	131.6	131.6	130	133	127	135	125	137
Takeoff Thrust to Weight Ratio	0.3093	0.3093	0.3093	0.29	0.32	0.27	0.34	0.25	0.36
Aspect Ratio - Lower Progress	9.1			9	10	9	11	9	12
Aspect Ratio - Medium Progress		9	10	9	11	9	12	9	13
Aspect Ratio - Higher Progress				9	12	9	13	9	14
Fan Pressure Ratio (MCR)	1.52	1.4	1.52	1.35	1.52	1.32	1.52	1.3	1.52
T40 (MCR) [R]	3091	3065	3115	3065	3200	3065	3300	3065	3400



Constraints

Constraint Parameter	Timeframe				
	2018 TRA	2018 Opt	2030	2040	2050
T3max Limit [R]	1649	1649	1800	1836	1872
Gate Constraint [ft]	110.6	118.1	118.1	118.1	118.1
Fan Diameter Constraint [ft]	6.2	6.8	6.8	6.8	6.8

The fan diameter constraint was to ensure at least 2 feet of engine ground clearance. A wing weight penalty of 4.4% was assumed if the gate constraint wing span exceeded the limit.

E.5 WIDE BODY

Design Parameters and Ranges

	Timeframe								
		2018		2030		2040		2050	
Design Parameter	TRA	Min	Max	Min	Max	Min	Max	Min	Max
Takeoff Wing Loading [lb/ft2]	129.9	129.9	129.9	129	131	127	133	125	135
Takeoff Thrust to Weight Ratio	0.275	0.275	0.275	0.27	0.29	0.26	0.3	0.25	0.31
Aspect Ratio – Lower Progress	8.9			8.5	10	8.5	11	8.5	12
Aspect Ratio – Medium Progress		8.5	10	8.5	10.5	8.5	11.5	8.5	12.5
Aspect Ratio – Higher Progress				8.5	11	8.5	12	8.5	13
Fan Pressure Ratio (MCR)	1.6	1.4	1.6	1.4	1.6	1.33	1.6	1.3	1.6
T40 (MCR) [R]	2848	2840	2940	2800	2940	2800	3070	2800	3140

Constraints

	Timeframe				
Constraint Parameter	**2018 TRA**	**2018 Opt**	**2030**	**2040**	**2050**
T3max Limit [R]	1680	1680	1815	1850	1895
Gate Constraint [ft]	212.5	213.3	213.3	213.3	213.3
Fan Diameter Constraint [ft]	9.8	10.9	10.9	10.9	10.9

The fan diameter constraint was to ensure at least 2 feet of engine ground clearance. A wing weight penalty of 6.6%, which corresponded to a 10% drag penalty, was assumed if the gate constraint wing span exceeded the limit.

ANNEX F. ATW DETAILED

This appendix provides the resulting 2030, 2040, and 2050 ATW results for each aircraft class, which expands upon the content presented in Section 5.3.

F.1 TURBOPROP ATWS RESULTS

F.1.1 FB/ATK Summary

ATW Turboprop FB/ATK Summary Using **Design Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	29,577	0.2058			
2030	**Lower Progress**	28,692	0.1929	-6.23%	-0.53%	-0.53%
	Medium Progress	28,077	0.1812	-11.96%	-1.06%	-1.06%
	Higher Progress	27,522	0.1730	-15.93%	-1.44%	-1.44%
2040	**Lower Progress**	28,050	0.1814	-11.86%	-0.57%	-0.62%
	Medium Progress	27,221	0.1691	-17.83%	-0.89%	-0.69%
	Higher Progress	26,595	0.1604	-22.05%	-1.13%	-0.75%
2050	**Lower Progress**	27,659	0.1758	-14.57%	-0.49%	-0.31%
	Medium Progress	26,876	0.1630	-20.76%	-0.72%	-0.36%
	Higher Progress	26,177	0.1541	-25.13%	-0.90%	-0.40%

ATW Turboprop FB/ATK Summary Using **R1 Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	29,577	0.1944			
2030	**Lower Progress**	28,692	0.1821	-6.32%	-0.54%	-0.54%
	Medium Progress	28,077	0.1714	-11.84%	-1.04%	-1.04%
	Higher Progress	27,522	0.1638	-15.73%	-1.42%	-1.42%
2040	**Lower Progress**	28,050	0.1715	-11.79%	-0.57%	-0.60%
	Medium Progress	27,221	0.1602	-17.59%	-0.88%	-0.67%
	Higher Progress	26,595	0.1524	-21.60%	-1.10%	-0.72%
2050	**Lower Progress**	27,659	0.1664	-14.41%	-0.48%	-0.30%
	Medium Progress	26,876	0.1547	-20.44%	-0.71%	-0.35%
	Higher Progress	26,177	0.1466	-24.61%	-0.88%	-0.39%

F.1.2 Design Mission Performance Summary

ATW Turboprop Design Mission Performance Summary

Timeframe	Technology Confidence Level	MTOM (kg)	CO_2 Metric Value (kg/km)	Trip Fuel (kg)	Beginning of Cruise Weight (kg)	Cruise SFC (lbm/lbf/hr)	Beginning of Cruise L/D
2018	**TRA**	29,577	0.501	3,413	29,043	0.495	16.68
2030	**Lower Progress**	28,692	0.468	3,413	28,168	0.478	16.59
	Medium Progress	28,077	0.437	3,200	27,600	0.462	16.86
	Higher Progress	27,522	0.416	3,003	27,075	0.453	17.16
2040	**Lower Progress**	28,050	0.439	2,867	27,569	0.467	16.97
	Medium Progress	27,221	0.407	3,006	26,783	0.453	17.38
	Higher Progress	26,595	0.382	2,802	26,193	0.443	17.81
2050	**Lower Progress**	27,659	0.424	2,657	27,195	0.466	17.27
	Medium Progress	26,876	0.391	2,913	26,462	0.449	17.75
	Higher Progress	26,177	0.364	2,701	25,798	0.438	18.22

F.1.3 Propulsion Summary

ATW Turboprop Propulsion Summary

Timeframe	Technology Confidence Level	OPR (MCL, ISA)	Max T3 (R) at Takeoff, ISA + 22C	Engine Pod Weight (lb)	Bare Engine Weight (lb)	T41 at SLS, ISA (R)	Thrust Per Engine (lbf) (SLS, ISA, MTO)
2018	**TRA**	17.6	1,341	1,835	1,577	2,955	10,141
2030	**Lower Progress**	18.7	1,363	1,677	1,442	3,015	10,434
	Medium Progress	21.6	1,424	1,635	1,406	3,032	10,458
	Higher Progress	24.5	1,479	1,597	1,373	3,060	10,466
2040	**Lower Progress**	19.7	1,384	1,634	1,404	3,073	10,465
	Medium Progress	23.5	1,461	1,579	1,358	3,099	10,468
	Higher Progress	27.4	1,531	1,537	1,321	3,115	10,464
2050	**Lower Progress**	19.7	1,384	1,605	1,379	3,097	10,476
	Medium Progress	23.5	1,461	1,553	1,335	3,124	10,468
	Higher Progress	27.5	1,531	1,507	1,296	3,152	10,454

F.1.4 Aircraft Summary

ATW Turboprop Aircraft Summary

Timeframe	Technology Confidence Level	MTOW (lb)	MEW (lb)	MLW (lb)	AR	W/S @ Takeoff (lb/ft2)	P/W @ Takeoff	Wing Area (ft2)	Wing Weight (lb)	Wing Span (Including Wingtip Devices) (ft)
2018	**TRA**	65,206	36,505	57,682	12.80	96.3	0.1400	679	5,984	93.2
2030	**Lower Progress**	63,256	35,271	56,202	12.80	95.0	0.1320	668	5,597	92.5
	Medium Progress	61,899	34,504	55,278	12.90	96.0	0.1315	647	5,315	91.3
	Higher Progress	60,676	33,684	54,355	13.00	97.0	0.1310	627	5,060	90.3
2040	**Lower Progress**	61,840	34,448	55,212	13.00	97.0	0.1315	639	5,295	91.2
	Medium Progress	60,011	33,229	53,834	13.20	99.0	0.1310	608	4,886	89.6
	Higher Progress	58,631	32,241	52,773	13.40	101.0	0.1305	582	4,543	88.3
2050	**Lower Progress**	60,978	33,871	54,555	13.20	99.0	0.1310	618	5,129	90.3
	Medium Progress	59,251	32,764	53,296	13.50	100.0	0.1305	594	4,743	89.6
	Higher Progress	57,711	31,629	52,086	13.75	102.0	0.1300	567	4,375	88.3

F.2 BUSINESS JET ATWS RESULTS

F.2.1 FB/ATK Summary

ATW Business Jet FB/ATK Summary Using **Design Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	46,992	0.6341			
2030	**Lower Progress**	43,802	0.6041	-4.74%	-0.40%	-0.40%
	Medium Progress	42,409	0.5740	-9.48%	-0.83%	-0.83%
	Higher Progress	41,861	0.5539	-12.66%	-1.12%	-1.12%
2040	**Lower Progress**	42,683	0.5709	-9.98%	-0.48%	-0.56%
	Medium Progress	40,964	0.5377	-15.21%	-0.75%	-0.65%
	Higher Progress	39,343	0.5067	-20.10%	-1.01%	-0.89%
2050	**Lower Progress**	41,302	0.5402	-14.82%	-0.50%	-0.55%
	Medium Progress	39,761	0.5078	-19.92%	-0.69%	-0.57%
	Higher Progress	38,037	0.4753	-25.04%	-0.90%	-0.64%

ATW Business Jet FB/ATK Summary Using **R1 Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	46,992	0.3403			
2030	**Lower Progress**	43,802	0.3253	-4.39%	-0.37%	-0.37%
	Medium Progress	42,409	0.3097	-8.99%	-0.78%	-0.78%
	Higher Progress	41,861	0.2990	-12.12%	-1.07%	-1.07%
2040	**Lower Progress**	42,683	0.3077	-9.58%	-0.46%	-0.56%
	Medium Progress	40,964	0.2905	-14.63%	-0.72%	-0.64%
	Higher Progress	39,343	0.2743	-19.39%	-0.98%	-0.86%
2050	**Lower Progress**	41,302	0.2916	-14.32%	-0.48%	-0.54%
	Medium Progress	39,761	0.2748	-19.24%	-0.67%	-0.55%
	Higher Progress	38,037	0.2578	-24.23%	-0.86%	-0.62%

F.2.2 Design Mission Performance Summary

ATW Business Jet Design Mission Performance Summary

Timeframe	Technology Confidence Level	MTOM (kg)	CO_2 Metric Value (kg/km)	Trip Fuel (kg)	Beginning of Cruise Weight (kg)	Cruise SFC (lbm/lbf/hr)	Beginning of Cruise L/D
2018	**TRA**	46,992	0.598	20,504	45,684	0.648	18.98
2030	**Lower Progress**	43,802	0.549	18,908	43,371	0.635	19.29
	Medium Progress	42,409	0.516	17,936	42,067	0.626	19.59
	Higher Progress	41,861	0.493	17,284	41,470	0.624	20.17
2040	**Lower Progress**	42,683	0.510	17,833	42,216	0.622	19.71
	Medium Progress	40,964	0.479	16,761	40,577	0.616	20.12
	Higher Progress	39,343	0.444	15,757	39,049	0.610	20.54
2050	**Lower Progress**	41,302	0.479	16,841	40,906	0.603	19.72
	Medium Progress	39,761	0.445	15,794	39,432	0.599	20.32
	Higher Progress	38,037	0.416	14,744	37,835	0.589	20.70

F.2.3 Propulsion Summary

ATW Business Jet Propulsion Summary

Timeframe	Technology Confidence Level	FPR (MCR, ISA)	OPR (MCL, ISA)	Max T3 (R) at Takeoff, ISA + 15	Fan Diameter (in)	Engine Pod Weight (lb)	Bare Engine Weight (lb)	T40 at MCL, ISA (R)	BPR at MCL, ISA	SLS Thrust Per Engine (lbf)
2018	**TRA**	1.700	30.4	1,507	50.0	5,515	3,866	2,693	4.22	17,018
2030	**Lower Progress**	1.670	31.2	1,510	49.6	4,887	3,387	2,791	4.79	15,954
	Medium Progress	1.660	32.3	1,522	49.9	4,738	3,267	2,817	4.99	15,846
	Higher Progress	1.650	33.4	1,535	50.2	5,230	3,639	2,844	5.18	15,763
2040	**Lower Progress**	1.640	34.5	1,549	50.4	5,166	3,590	2,877	5.30	15,635
	Medium Progress	1.630	35.6	1,558	49.9	4,903	3,392	2,895	5.43	15,118
	Higher Progress	1.620	36.7	1,569	49.6	4,647	3,198	2,937	5.64	14,663
2050	**Lower Progress**	1.610	41.0	1,616	50.4	4,831	3,328	2,951	5.62	14,904
	Medium Progress	1.600	43.2	1,636	50.8	4,800	3,299	2,964	5.77	14,922
	Higher Progress	1.590	45.4	1,655	50.3	4,567	3,128	3,002	5.90	14,357

F.2.4 Aircraft Summary

ATW Business Jet Aircraft Summary

Timeframe	**Technology Confidence Level**	**MTOW (lb)**	**MEW (lb)**	**MLW (lb)**	**AR**	**W/S @ Takeoff (lb/ft2)**	**T/W @ Takeoff**	**Wing Area (ft2)**	**Wing Weight (lb)**	**Wing Span (Including Wingtip Devices) (ft)**	**Nacelle Diameter (ft)**	**Nacelle Length (ft)**
2018	**TRA**	103,600	50,668	55,800	7.73	44.5	0.932	1,283	12,943	99.6	5.6	16.9
2030	**Lower Progress**	96,567	49,106	53,991	8.20	44.5	0.932	1,236	12,556	100.7	5.6	16.0
	Medium Progress	93,496	48,268	53,061	8.50	44.5	0.932	1,190	12,303	100.6	5.6	15.9
	Higher Progress	92,287	48,545	53,286	8.75	44.5	0.932	1,172	12,053	101.3	5.7	16.7
2040	**Lower Progress**	94,101	49,146	53,888	8.40	44.5	0.932	1,236	12,334	101.9	5.7	16.6
	Medium Progress	90,310	47,843	52,457	8.70	44.5	0.932	1,181	11,911	101.4	5.6	16.2
	Higher Progress	86,736	46,582	51,092	9.00	44.5	0.932	1,132	11,498	100.9	5.6	15.9
2050	**Lower Progress**	91,056	48,454	53,024	8.50	44.5	0.932	1,209	12,266	101.4	5.7	16.2
	Medium Progress	87,657	47,424	51,932	8.90	44.5	0.932	1,150	11,800	101.2	5.7	16.1
	Higher Progress	83,858	46,063	50,442	9.20	44.5	0.932	1,087	11,346	100.0	5.7	15.8

F.3 REGIONAL JET ATWS RESULTS

F.3.1 FB/ATK Summary

ATW Regional Jet FB/ATK Summary Using **Design Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	56,400	0.1726			
2030	**Lower Progress**	55,390	0.1677	-2.87%	-0.24%	-0.24%
	Medium Progress	54,539	0.1613	-6.55%	-0.56%	-0.56%
	Higher Progress	53,356	0.1534	-11.14%	-0.98%	-0.98%
2040	**Lower Progress**	54,371	0.1577	-8.65%	-0.41%	-0.61%
	Medium Progress	53,053	0.1483	-14.12%	-0.69%	-0.84%
	Higher Progress	52,012	0.1410	-18.35%	-0.92%	-0.84%
2050	**Lower Progress**	53,713	0.1494	-13.49%	-0.45%	-0.54%
	Medium Progress	52,505	0.1418	-17.85%	-0.61%	-0.44%
	Higher Progress	51,549	0.1356	-21.44%	-0.75%	-0.38%

ATW Regional Jet FB/ATK Summary Using **R1 Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	56,400	0.1377			
2030	**Lower Progress**	55,390	0.1338	-2.83%	-0.24%	-0.24%
	Medium Progress	54,539	0.1289	-6.40%	-0.55%	-0.55%
	Higher Progress	53,356	0.1228	-10.86%	-0.95%	-0.95%
2040	**Lower Progress**	54,371	0.1260	-8.51%	-0.40%	-0.60%
	Medium Progress	53,053	0.1186	-13.90%	-0.68%	-0.83%
	Higher Progress	52,012	0.1128	-18.10%	-0.90%	-0.84%
2050	**Lower Progress**	53,713	0.1196	-13.18%	-0.44%	-0.52%
	Medium Progress	52,505	0.1134	-17.63%	-0.60%	-0.44%
	Higher Progress	51,549	0.1087	-21.09%	-0.74%	-0.37%

F.3.2 Design Mission Performance Summary

ATW Regional Jet Design Mission Performance Summary

Timeframe	Technology Confidence Level	MTOM (kg)	CO_2 Metric Value (kg/km)	Trip Fuel (kg)	Beginning of Cruise Weight (kg)	Cruise SFC (lbm/lbf/hr)	Beginning of Cruise L/D
2018	**TRA**	56,400	0.629	12,253	55,266	0.555	18.23
2030	**Lower Progress**	55,390	0.609	11,900	54,149	0.550	18.29
	Medium Progress	54,539	0.594	11,450	53,366	0.544	18.62
	Higher Progress	53,356	0.566	10,888	52,251	0.537	18.96
2040	**Lower Progress**	54,371	0.576	11,193	53,199	0.537	18.80
	Medium Progress	53,053	0.537	10,523	51,966	0.531	19.50
	Higher Progress	52,012	0.512	10,004	50,999	0.527	20.13
2050	**Lower Progress**	53,713	0.538	10,600	52,667	0.527	19.38
	Medium Progress	52,505	0.510	10,066	51,462	0.523	20.06
	Higher Progress	51,549	0.487	9,626	50,599	0.518	20.48

F.3.3 Propulsion Summary

ATW Regional Jet Propulsion Summary

Timeframe	Technology Confidence Level	FPR (MCR, ISA)	OPR (MCL, ISA)	Max T3 (R) at Takeoff, ISA + 15	Fan Diameter (in)	Engine Pod Weight (lb)	Bare Engine Weight (lb)	T40 at MCL, ISA (R)	BPR at MCL, ISA	SLS Thrust Per Engine (lbf)
2018	**TRA**	1.500	45.3	1,635	73.0	5,324	3,696	3,057	11.15	23,814
2030	**Lower Progress**	1.481	46.0	1,639	72.9	5,212	3,615	3,079	11.84	22,938
	Medium Progress	1.470	48.0	1,652	73.4	5,181	3,582	3,063	12.20	22,771
	Higher Progress	1.461	50.0	1,662	73.6	5,063	3,491	3,052	12.67	22,446
2040	**Lower Progress**	1.450	46.0	1,626	74.1	5,202	3,596	3,061	13.20	22,283
	Medium Progress	1.440	50.0	1,658	74.4	5,086	3,505	3,073	13.61	22,007
	Higher Progress	1.430	53.0	1,679	75.2	5,038	3,463	3,097	14.20	21,990
2050	**Lower Progress**	1.440	48.0	1,633	76.5	5,332	3,688	3,071	14.29	23,233
	Medium Progress	1.430	53.0	1,677	75.1	5,049	3,479	3,057	14.38	21,925
	Higher Progress	1.416	57.0	1,702	77.3	5,190	3,569	3,053	15.05	22,542

F.3.4 Aircraft Summary

ATW Regional Jet Aircraft Summary

Timeframe	**Technology Confidence Level**	**MTOW (lb)**	**MEW (lb)**	**MLW (lb)**	**AR**	**W/S @ Takeoff (lb/ft2)**	**T/W @ Takeoff**	**Wing Area (ft2)**	**Wing Weight (lb)**	**Wing Span (Including Wingtip Devices) (ft)**	**Nacelle Diameter (ft)**	**Nacelle Length (ft)**
2018	**TRA**	124,341	68,654	108,137	11.03	112.6	0.382	1,109	12,684	105.1	7.2	11.5
2030	**Lower Progress**	122,114	67,344	106,683	11.00	110.2	0.375	1,113	12,056	105.1	7.2	11.3
	Medium Progress	120,239	66,585	105,796	11.23	110.1	0.379	1,096	11,714	105.4	7.3	11.4
	Higher Progress	117,631	65,380	104,423	11.41	110.2	0.380	1,071	11,258	105.0	7.3	11.3
2040	**Lower Progress**	119,867	66,893	105,988	11.45	108.4	0.372	1,109	11,902	107.1	7.3	11.3
	Medium Progress	116,961	65,646	104,556	12.28	108.3	0.375	1,084	11,618	109.6	7.4	11.2
	Higher Progress	114,666	64,625	103,400	13.00	108.6	0.382	1,059	11,288	111.5	7.4	11.1
2050	**Lower Progress**	118,417	66,868	105,850	12.50	114.5	0.392	1,038	11,952	108.2	7.6	11.1
	Medium Progress	115,754	65,578	104,352	13.00	106.5	0.377	1,091	11,819	113.1	7.4	11.0
	Higher Progress	113,646	64,523	103,214	13.50	110.5	0.395	1,031	11,115	112.1	7.6	11.0

F.4 NARROW BODY ATWS RESULTS

F.4.1 FB/ATK Summary

ATW Narrow Body FB/ATK Summary Using **Design Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	79,000	0.1575			
2030	**Lower Progress**	76,252	0.1512	-3.99%	-0.34%	-0.34%
	Medium Progress	74,411	0.1405	-10.78%	-0.95%	-0.95%
	Higher Progress	72,684	0.1303	-17.26%	-1.57%	-1.57%
2040	**Lower Progress**	74,105	0.1369	-13.10%	-0.64%	-0.99%
	Medium Progress	72,492	0.1278	-18.87%	-0.95%	-0.95%
	Higher Progress	70,833	0.1194	-24.21%	-1.25%	-0.87%
2050	**Lower Progress**	73,210	0.1281	-18.68%	-0.64%	-0.66%
	Medium Progress	71,135	0.1194	-24.20%	-0.86%	-0.68%
	Higher Progress	69,623	0.1134	-27.97%	-1.02%	-0.51%

ATW Narrow Body FB/ATK Summary Using **R1 Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	79,000	0.1327			
2030	**Lower Progress**	76,252	0.1276	-3.85%	-0.33%	-0.33%
	Medium Progress	74,411	0.1190	-10.34%	-0.91%	-0.91%
	Higher Progress	72,684	0.1105	-16.72%	-1.51%	-1.51%
2040	**Lower Progress**	74,105	0.1159	-12.63%	-0.61%	-0.95%
	Medium Progress	72,492	0.1084	-18.33%	-0.92%	-0.93%
	Higher Progress	70,833	0.1013	-23.66%	-1.22%	-0.87%
2050	**Lower Progress**	73,210	0.1085	-18.23%	-0.63%	-0.66%
	Medium Progress	71,135	0.1012	-23.75%	-0.84%	-0.68%
	Higher Progress	69,623	0.0962	-27.54%	-1.00%	-0.52%

F.4.2 Design Mission Performance Summary

ATW Narrow Body Design Mission Performance Summary

Timeframe	Technology Confidence Level	MTOM (kg)	CO_2 Metric Value (kg/km)	Trip Fuel (kg)	Beginning of Cruise Weight (kg)	Cruise SFC (lbm/lbf/hr)	Beginning of Cruise L/D
2018	**TRA**	79,000	0.810	16,985	77,571	0.535	17.35
2030	**Lower Progress**	76,252	0.757	15,903	75,134	0.529	18.09
	Medium Progress	74,411	0.694	14,750	73,401	0.524	18.95
	Higher Progress	72,684	0.633	13,650	71,703	0.515	19.88
2040	**Lower Progress**	74,105	0.671	14,357	73,111	0.515	19.09
	Medium Progress	72,492	0.619	13,376	71,521	0.510	20.09
	Higher Progress	70,833	0.575	12,470	69,950	0.501	20.79
2050	**Lower Progress**	73,210	0.625	13,408	72,214	0.506	20.09
	Medium Progress	71,135	0.574	12,470	70,144	0.502	20.93
	Higher Progress	69,623	0.536	11,830	68,720	0.497	21.59

F.4.3 Propulsion Summary

ATW Narrow Body Propulsion Summary

Timeframe	Technology Confidence Level	FPR (MCR, ISA)	OPR (MCL, ISA)	Max T3 (R) at Takeoff, ISA + 15	Fan Diameter (in)	Engine Pod Weight (lb)	Bare Engine Weight (lb)	T40 at MCL, ISA (R)	BPR at MCL, ISA	SLS Thrust Per Engine (lbf)
2018	**TRA**	1.520	46.9	1,639	81.0	5,744	4,703	3,094	11.35	27,076
2030	**Lower Progress**	1.515	47.0	1,636	80.0	5,497	4,491	3,150	11.79	26,153
	Medium Progress	1.500	49.0	1,650	80.5	5,336	4,349	3,167	12.51	25,738
	Higher Progress	1.487	52.0	1,668	81.0	5,238	4,254	3,122	12.99	25,389
2040	**Lower Progress**	1.494	49.0	1,643	80.5	5,316	4,333	3,112	12.89	25,378
	Medium Progress	1.481	53.0	1,673	81.0	5,146	4,174	3,169	13.71	25,067
	Higher Progress	1.465	56.0	1,691	82.0	5,162	4,174	3,102	14.25	24,826
2050	**Lower Progress**	1.482	54.0	1,680	81.0	5,133	4,163	3,240	14.34	25,067
	Medium Progress	1.469	57.0	1,700	81.4	5,042	4,075	3,198	14.78	24,661
	Higher Progress	1.457	61.0	1,725	82.3	5,032	4,055	3,119	14.95	24,546

F.4.4 Aircraft Summary

ATW Narrow Body Aircraft Summary

Timeframe	Technology Confidence Level	MTOW (lb)	MEW (lb)	MLW (lb)	AR	W/S @ Takeoff (lb/ft2)	T/W @ Takeoff	Wing Area (ft2)	Wing Weight (lb)	Wing Span (Including Wingtip Devices) (ft)	Nacelle Diameter (ft)	Nacelle Length (ft)
2018	**TRA**	174,165	93,240	148,591	9.10	131.6	0.309	1,331	14,772	106.3	8.4	11.5
2030	**Lower Progress**	168,107	90,486	145,556	10.00	130.9	0.309	1,296	13,942	109.9	8.3	11.3
	Medium Progress	164,049	89,259	144,036	11.00	130.1	0.312	1,273	13,958	114.3	8.3	10.9
	Higher Progress	160,242	88,168	142,651	12.00	130.1	0.315	1,243	13,896	118.0	8.4	10.9
2040	**Lower Progress**	163,374	89,576	144,226	11.00	127.9	0.309	1,289	14,077	115.0	8.3	10.9
	Medium Progress	159,817	88,439	142,828	12.00	128.5	0.312	1,255	14,436	118.5	8.4	10.7
	Higher Progress	156,160	87,032	141,165	12.75	127.2	0.315	1,238	14,015	121.4	8.5	10.8
2050	**Lower Progress**	161,400	89,934	144,339	12.00	125.3	0.309	1,299	15,157	120.6	8.4	10.7
	Medium Progress	156,827	87,729	141,831	12.95	125.9	0.311	1,256	14,575	123.2	8.4	10.7
	Higher Progress	153,492	85,941	139,904	13.60	125.8	0.317	1,231	13,922	125.0	8.5	10.7

F.5 WIDE BODY ATWS RESULTS

F.5.1 FB/ATK Summary

ATW Wide Body FB/ATK Summary Using **Design Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	280,000	0.1979			
2030	**Lower Progress**	276,585	0.1905	-3.73%	-0.32%	-0.32%
	Medium Progress	267,442	0.1794	-9.35%	-0.81%	-0.81%
	Higher Progress	253,440	0.1648	-16.70%	-1.51%	-1.51%
2040	**Lower Progress**	268,138	0.1694	-14.38%	-0.70%	-1.17%
	Medium Progress	255,106	0.1543	-22.02%	-1.12%	-1.49%
	Higher Progress	240,933	0.1399	-29.30%	-1.56%	-1.63%
2050	**Lower Progress**	260,628	0.1561	-21.11%	-0.74%	-0.82%
	Medium Progress	247,160	0.1429	-27.76%	-1.01%	-0.76%
	Higher Progress	233,211	0.1304	-34.07%	-1.29%	-0.70%

ATW Wide Body FB/ATK Summary Using **R1 Range**

Timeframe	Technology Confidence Level	MTOM (kg)	FB/ATK at Design Range (kg/ATK)	% FB/ATK Rel. 2018 TRA	FB/ATK (Rel. 2018 TRA) Per Annum	FB/ATK (Rel. Previous Decade) Per Annum
2018	**TRA**	280,000	0.1251			
2030	**Lower Progress**	276,585	0.1208	-3.43%	-0.29%	-0.29%
	Medium Progress	267,442	0.1141	-8.78%	-0.76%	-0.76%
	Higher Progress	253,440	0.1054	-15.75%	-1.42%	-1.42%
2040	**Lower Progress**	268,138	0.1081	-13.60%	-0.66%	-1.11%
	Medium Progress	255,106	0.0990	-20.89%	-1.06%	-1.41%
	Higher Progress	240,933	0.0902	-27.90%	-1.48%	-1.55%
2050	**Lower Progress**	260,628	0.0999	-20.16%	-0.70%	-0.79%
	Medium Progress	247,160	0.0919	-26.57%	-0.96%	-0.74%
	Higher Progress	233,211	0.0842	-32.68%	-1.23%	-0.68%

F.5.2 Design Mission Performance Summary

ATW Wide Body Design Mission Performance Summary

Timeframe	Technology Confidence Level	MTOM (kg)	CO$_2$ Metric Value (kg/km)	Trip Fuel (kg)	Beginning of Cruise Weight (kg)	Cruise SFC (lbm/lbf/hr)	Beginning of Cruise L/D
2018	**TRA**	280,000	1.685	100,972	274,096	0.522	20.29
2030	**Lower Progress**	276,585	1.561	95,632	269,253	0.514	20.94
	Medium Progress	267,442	1.462	89,954	260,481	0.504	21.27
	Higher Progress	253,440	1.332	82,529	247,154	0.493	21.64
2040	**Lower Progress**	268,138	1.374	84,880	261,758	0.495	22.36
	Medium Progress	255,106	1.226	77,160	248,530	0.487	23.29
	Higher Progress	240,933	1.104	69,811	234,841	0.478	24.10
2050	**Lower Progress**	260,628	1.242	78,075	253,957	0.488	23.70
	Medium Progress	247,160	1.130	71,368	240,915	0.479	24.44
	Higher Progress	233,211	1.027	64,992	227,357	0.474	25.17

F.5.3 Propulsion Summary

ATW Wide Body Propulsion Summary

Timeframe	Technology Confidence Level	FPR (MCR, ISA)	OPR (MCL, ISA)	Max T3 (R) at Takeoff, ISA + 15	Fan Diameter (in)	Engine Pod Weight (lb)	Bare Engine Weight (lb)	T40 at MCL, ISA (R)	BPR at MCL, ISA	SLS Thrust Per Engine (lbf)
2018	**TRA**	1.600	47.0	1,679	118.0	19,590	15,269	3,051	9.12	85,202
2030	**Lower Progress**	1.593	54.0	1,740	117.0	19,258	15,006	3,046	9.19	82,706
	Medium Progress	1.570	59.0	1,774	117.0	19,518	15,216	2,992	9.32	79,851
	Higher Progress	1.547	66.0	1,817	119.2	18,949	14,683	3,041	10.00	79,783
2040	**Lower Progress**	1.536	57.0	1,745	124.8	21,171	16,507	3,143	11.14	86,344
	Medium Progress	1.507	64.0	1,792	125.3	20,364	15,796	3,133	11.66	83,063
	Higher Progress	1.479	69.0	1,817	124.4	19,318	14,929	3,179	12.59	77,858
2050	**Lower Progress**	1.516	61.0	1,770	126.0	20,377	15,817	3,179	11.88	85,202
	Medium Progress	1.490	68.0	1,817	124.3	19,261	14,883	3,265	12.74	79,340
	Higher Progress	1.470	72.0	1,835	122.4	17,827	13,700	3,218	13.10	74,075

F.5.4 Aircraft Summary

ATW Wide Body Aircraft Summary

Timeframe	Technology Confidence Level	MTOW (lb)	MEW (lb)	MLW (lb)	AR	W/S @ Takeoff (lb/ft2)	T/W @ Takeoff	Wing Area (ft2)	Wing Weight (lb)	Wing Span (Including Wingtip Devices) (ft)	Nacelle Diameter (ft)	Nacelle Length (ft)
2018	**TRA**	617,295	306,311	456,357	8.90	129.9	0.275	4,768	67,939	206.0	11.4	17.7
2030	**Lower Progress**	609,766	307,131	456,747	9.49	127.1	0.272	4,783	72,175	213.0	11.3	17.7
	Medium Progress	589,610	300,135	449,098	9.75	128.4	0.272	4,576	67,868	211.2	11.3	17.5
	Higher Progress	558,741	286,330	434,586	10.00	127.4	0.287	4,371	58,820	209.1	11.5	17.6
2040	**Lower Progress**	591,144	313,114	461,807	10.84	127.5	0.293	4,622	75,087	223.8	12.0	17.9
	Medium Progress	562,414	302,212	450,085	11.45	127.1	0.297	4,408	70,343	224.7	12.0	17.9
	Higher Progress	531,166	288,402	434,990	11.86	128.6	0.295	4,111	63,753	220.8	11.9	17.2
2050	**Lower Progress**	574,587	312,253	460,235	11.86	125.4	0.295	4,565	77,673	232.7	12.1	17.7
	Medium Progress	544,894	298,236	445,308	12.30	125.4	0.293	4,328	70,872	230.7	11.9	17.2
	Higher Progress	514,142	282,643	428,571	12.68	126.2	0.290	4,055	63,729	226.8	11.8	16.8

ANNEX G. COMPLETE ENERGY INTENSITY TIMELINES FOR EACH VEHICLE CLASS

This appendix provides the complete input for MDG for each progress level, year, vehicle type, and vehicle class. The tables cover each year between 2018 (baseline TRA year) and 2070 (final year for the MDG fleet analysis). Due to the size of the data, tables are split into each vehicle class below. Each vehicle class table have nine columns for the energy intensity factors: three progress levels times three vehicle types. For all tables the first row corresponds to the 2018 TRA; therefore, the ATW-T1 has the same energy intensity factor of 100% in 2018, i.e. it has the same energy intensity. Lower energy intensity factors correspond to more efficient aircraft and using the factors and the TRA energy intensity figures from the plots in APPENDIX M3.7, raw energy intensity figures can be calculated. Energy intensity tables are not provided for brevity and were not needed for the MDG analyses.

G.1 TURBOPROP ENERGY INTENSITY FACTORS NORMALIZED BY 2018 TRA

	ATW-T1			ACA-T2			ACA-T3		
Year	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress
2018	100.0%	100.0%	100.0%	—	—	—	—	—	—
2019	99.47%	98.94%	98.56%	—	—	—	—	—	—
2020	98.93%	97.90%	97.15%	—	—	—	—	—	—
2021	98.40%	96.87%	95.76%	—	—	—	—	—	—
2022	97.88%	95.84%	94.38%	—	—	—	—	—	—
2023	97.35%	94.83%	93.03%	—	—	—	—	—	—
2024	96.83%	93.83%	91.69%	—	—	—	—	—	—
2025	96.32%	92.84%	90.37%	—	—	—	—	—	—
2026	95.80%	91.86%	89.08%	—	—	—	—	—	—
2027	95.29%	90.89%	87.80%	—	—	—	—	—	—
2028	94.78%	89.93%	86.54%	—	—	—	—	—	—
2029	94.27%	88.98%	85.30%	—	—	—	—	—	—
2030	93.77%	88.04%	84.07%	—	—	—	—	—	—
2031	93.19%	87.43%	83.44%	—	—	—	—	—	—
2032	92.62%	86.83%	82.81%	—	—	—	—	—	—
2033	92.04%	86.23%	82.19%	—	—	—	—	—	—
2034	91.48%	85.64%	81.57%	—	—	—	—	—	—
2035	90.91%	85.05%	80.95%	86.37%	76.55%	68.81%	100.0%	85.05%	72.86%
2036	90.35%	84.47%	80.35%	85.83%	76.02%	68.02%	99.39%	84.47%	72.31%
2037	89.79%	83.89%	79.74%	85.30%	75.50%	67.23%	98.77%	83.89%	71.77%
2038	89.24%	83.31%	79.14%	84.78%	74.98%	66.46%	98.16%	83.31%	71.23%
2039	88.69%	82.74%	78.54%	84.25%	74.47%	65.69%	97.56%	82.74%	70.69%
2040	88.14%	82.17%	77.95%	83.73%	73.95%	64.93%	96.95%	82.17%	70.16%
2041	87.87%	81.87%	77.64%	83.47%	73.68%	64.41%	96.65%	81.87%	69.88%

2042	87.59%	81.57%	77.33%	83.21%	73.42%	63.89%	96.35%	81.57%	69.59%
2043	87.32%	81.28%	77.02%	82.95%	73.15%	63.38%	96.05%	81.28%	69.31%
2044	87.05%	80.98%	76.71%	82.70%	72.89%	62.87%	95.75%	80.98%	69.04%
2045	86.78%	80.69%	76.40%	82.44%	72.62%	62.37%	95.45%	80.69%	68.76%
2046	86.51%	80.40%	76.09%	82.18%	72.36%	61.86%	95.16%	80.40%	68.48%
2047	86.24%	80.10%	75.78%	81.92%	72.09%	61.37%	94.86%	80.10%	68.21%
2048	85.97%	79.81%	75.48%	81.67%	71.83%	60.87%	94.56%	79.81%	67.93%
2049	85.70%	79.52%	75.18%	81.42%	71.57%	60.38%	94.27%	79.52%	67.66%
2050	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2051	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2052	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2053	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2054	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2055	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2056	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2057	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2058	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2059	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2060	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2061	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2062	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2063	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2064	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2065	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2066	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2067	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2068	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%

2069	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%
2070	85.43%	79.24%	74.87%	81.16%	71.31%	59.90%	93.98%	79.24%	67.39%

G.2 BUSINESS JET ENERGY INTENSITY FACTORS NORMALIZED BY 2018 TRA

	ATW-T1			ACA-T2			ACA-T3		
Year	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress
2018	100.0%	100.0%	100.0%	—	—	—	—	—	—
2019	99.60%	99.17%	98.88%	—	—	—	—	—	—
2020	99.19%	98.35%	97.77%	—	—	—	—	—	—
2021	98.79%	97.54%	96.67%	—	—	—	—	—	—
2022	98.40%	96.74%	95.59%	—	—	—	—	—	—
2023	98.00%	95.94%	94.52%	—	—	—	—	—	—
2024	97.60%	95.14%	93.46%	—	—	—	—	—	—
2025	97.21%	94.36%	92.41%	—	—	—	—	—	—
2026	96.82%	93.58%	91.37%	—	—	—	—	—	—
2027	96.43%	92.80%	90.35%	—	—	—	—	—	—
2028	96.04%	92.04%	89.34%	—	—	—	—	—	—
2029	95.65%	91.28%	88.33%	—	—	—	—	—	—
2030	95.26%	90.52%	87.34%	—	—	—	—	—	—
2031	94.73%	89.93%	86.57%	—	—	—	—	—	—
2032	94.19%	89.35%	85.80%	—	—	—	—	—	—
2033	93.66%	88.76%	85.04%	—	—	—	—	—	—
2034	93.13%	88.19%	84.29%	—	—	—	—	—	—
2035	92.61%	87.61%	83.54%	90.29%	83.23%	77.27%	—	—	—
2036	92.08%	87.04%	82.80%	89.78%	82.69%	76.45%	—	—	—
2037	91.56%	86.47%	82.06%	89.28%	82.15%	75.63%	—	—	—
2038	91.05%	85.91%	81.34%	88.77%	81.61%	74.82%	—	—	—

2039	90.53%	85.35%	80.61%	88.27%	81.08%	74.03%	—	—	—
2040	90.02%	84.79%	79.90%	87.77%	80.55%	73.24%	103.5%	89.03%	79.90%
2041	89.53%	84.31%	79.39%	87.29%	80.09%	72.64%	103.0%	88.52%	79.39%
2042	89.03%	83.83%	78.89%	86.81%	79.64%	72.04%	102.4%	88.02%	78.89%
2043	88.54%	83.35%	78.38%	86.33%	79.18%	71.45%	101.8%	87.52%	78.38%
2044	88.05%	82.87%	77.89%	85.85%	78.73%	70.87%	101.3%	87.02%	77.89%
2045	87.57%	82.40%	77.39%	85.38%	78.28%	70.29%	100.7%	86.52%	77.39%
2046	87.09%	81.93%	76.90%	84.91%	77.83%	69.72%	100.1%	86.03%	76.90%
2047	86.61%	81.46%	76.41%	84.44%	77.39%	69.15%	99.60%	85.54%	76.41%
2048	86.13%	81.00%	75.92%	83.98%	76.95%	68.58%	99.05%	85.05%	75.92%
2049	85.66%	80.54%	75.44%	83.51%	76.51%	68.02%	98.50%	84.56%	75.44%
2050	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2051	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2052	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2053	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2054	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2055	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2056	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2057	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2058	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2059	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2060	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2061	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2062	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2063	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2064	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2065	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%

2066	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2067	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2068	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2069	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%
2070	85.18%	80.08%	74.96%	83.05%	76.07%	67.46%	97.96%	84.08%	74.96%

G.3 REGIONAL JET ENERGY INTENSITY FACTORS NORMALIZED BY 2018 TRA

	ATW-T1			ACA-T2			ACA-T3		
Year	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress
2018	100.0%	100.0%	100.0%	—	—	—	—	—	—
2019	99.76%	99.44%	99.02%	—	—	—	—	—	—
2020	99.51%	98.88%	98.05%	—	—	—	—	—	—
2021	99.27%	98.32%	97.09%	—	—	—	—	—	—
2022	99.03%	97.77%	96.14%	—	—	—	—	—	—
2023	98.79%	97.22%	95.20%	—	—	—	—	—	—
2024	98.55%	96.67%	94.27%	—	—	—	—	—	—
2025	98.31%	96.13%	93.34%	—	—	—	—	—	—
2026	98.07%	95.59%	92.43%	—	—	—	—	—	—
2027	97.84%	95.05%	91.52%	—	—	—	—	—	—
2028	97.60%	94.51%	90.63%	—	—	—	—	—	—
2029	97.36%	93.98%	89.74%	—	—	—	—	—	—
2030	97.13%	93.45%	88.86%	—	—	—	—	—	—
2031	96.53%	92.67%	88.11%	—	—	—	—	—	—
2032	95.94%	91.89%	87.37%	—	—	—	—	—	—
2033	95.35%	91.11%	86.63%	—	—	—	—	—	—
2034	94.77%	90.35%	85.90%	—	—	—	—	—	—
2035	94.19%	89.59%	85.18%	89.48%	80.63%	72.40%	113.0%	103.0%	80.92%

2036	93.62%	88.83%	84.46%	88.94%	79.95%	71.50%	112.3%	102.2%	80.24%
2037	93.04%	88.09%	83.75%	88.39%	79.28%	70.61%	111.7%	101.3%	79.56%
2038	92.48%	87.34%	83.04%	87.85%	78.61%	69.74%	111.0%	100.5%	78.89%
2039	91.91%	86.61%	82.34%	87.32%	77.95%	68.87%	110.3%	99.60%	78.23%
2040	91.35%	85.88%	81.65%	86.78%	77.29%	68.01%	109.6%	98.76%	77.57%
2041	90.85%	85.50%	81.34%	86.31%	76.95%	67.48%	109.0%	98.33%	77.27%
2042	90.36%	85.12%	81.02%	85.84%	76.61%	66.95%	108.4%	97.89%	76.97%
2043	89.87%	84.74%	80.71%	85.38%	76.27%	66.42%	107.8%	97.46%	76.67%
2044	89.38%	84.37%	80.40%	84.91%	75.93%	65.90%	107.3%	97.03%	76.38%
2045	88.90%	84.00%	80.09%	84.45%	75.60%	65.38%	106.7%	96.60%	76.09%
2046	88.41%	83.62%	79.78%	83.99%	75.26%	64.87%	106.1%	96.17%	75.79%
2047	87.94%	83.25%	79.47%	83.54%	74.93%	64.36%	105.5%	95.74%	75.50%
2048	87.46%	82.89%	79.17%	83.08%	74.60%	63.85%	105.0%	95.32%	75.21%
2049	86.98%	82.52%	78.86%	82.63%	74.27%	63.35%	104.4%	94.90%	74.92%
2050	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2051	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2052	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2053	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2054	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2055	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2056	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2057	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2058	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2059	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2060	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2061	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2062	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%

2063	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2064	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2065	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2066	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2067	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2068	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2069	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%
2070	86.51%	82.15%	78.56%	82.19%	73.94%	62.85%	103.8%	94.48%	74.63%

G.4 NARROW BODY ENERGY INTENSITY FACTORS NORMALIZED BY 2018 TRA

	ATW-T1			ACA-T2			ACA-T3		
Year	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress
2018	100.0%	100.0%	100.0%	—	—	—	—	—	—
2019	99.66%	99.05%	98.43%	—	—	—	—	—	—
2020	99.32%	98.12%	96.89%	—	—	—	—	—	—
2021	98.99%	97.19%	95.37%	—	—	—	—	—	—
2022	98.65%	96.27%	93.88%	—	—	—	—	—	—
2023	98.32%	95.36%	92.41%	—	—	—	—	—	—
2024	97.98%	94.46%	90.96%	—	—	—	—	—	—
2025	97.65%	93.56%	89.54%	—	—	—	—	—	—
2026	97.32%	92.68%	88.14%	—	—	—	—	—	—
2027	96.99%	91.80%	86.75%	—	—	—	—	—	—
2028	96.66%	90.93%	85.40%	—	—	—	—	—	—
2029	96.33%	90.07%	84.06%	—	—	—	—	—	—
2030	96.01%	89.22%	82.74%	—	—	—	—	—	—
2031	95.05%	88.38%	82.02%	—	—	—	—	—	—
2032	94.11%	87.54%	81.30%	—	—	—	—	—	—

2033	93.18%	86.71%	80.59%	—	—	—	—	—	—
2034	92.25%	85.89%	79.89%	—	—	—	—	—	—
2035	91.34%	85.08%	79.19%	86.77%	76.57%	67.31%	109.6%	97.84%	75.23%
2036	90.43%	84.27%	78.50%	85.91%	75.84%	66.46%	108.5%	96.91%	74.57%
2037	89.54%	83.47%	77.81%	85.06%	75.13%	65.61%	107.4%	96.00%	73.92%
2038	88.65%	82.68%	77.13%	84.22%	74.42%	64.77%	106.4%	95.09%	73.28%
2039	87.77%	81.90%	76.46%	83.38%	73.71%	63.95%	105.3%	94.19%	72.64%
2040	86.90%	81.13%	75.79%	82.56%	73.01%	63.14%	104.3%	93.30%	72.00%
2041	86.33%	80.58%	75.41%	82.01%	72.52%	62.56%	103.6%	92.66%	71.64%
2042	85.76%	80.03%	75.02%	81.47%	72.03%	61.99%	102.9%	92.04%	71.27%
2043	85.19%	79.49%	74.64%	80.93%	71.54%	61.43%	102.2%	91.41%	70.91%
2044	84.62%	78.95%	74.26%	80.39%	71.06%	60.87%	101.5%	90.79%	70.55%
2045	84.06%	78.42%	73.89%	79.86%	70.57%	60.32%	100.9%	90.18%	70.19%
2046	83.51%	77.88%	73.51%	79.33%	70.10%	59.77%	100.2%	89.57%	69.83%
2047	82.95%	77.36%	73.14%	78.81%	69.62%	59.22%	99.54%	88.96%	69.48%
2048	82.40%	76.83%	72.76%	78.28%	69.15%	58.68%	98.89%	88.36%	69.13%
2049	81.86%	76.31%	72.39%	77.77%	68.68%	58.15%	98.23%	87.76%	68.77%
2050	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2051	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2052	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2053	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2054	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2055	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2056	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2057	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2058	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2059	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%

2060	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2061	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2062	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2063	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2064	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2065	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2066	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2067	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2068	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2069	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%
2070	81.32%	75.80%	72.03%	77.25%	68.22%	57.62%	97.58%	87.17%	68.43%

G.5 WIDE BODY ENERGY INTENSITY FACTORS NORMALIZED BY 2018 TRA

	ATW-T1			ACA-T2			ACA-T3		
Year	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress	Lower Progress	Medium Progress	Higher Progress
2018	100.0%	100.0%	100.0%	—	—	—	—	—	—
2019	99.68%	99.19%	98.49%	—	—	—	—	—	—
2020	99.37%	98.38%	97.00%	—	—	—	—	—	—
2021	99.05%	97.58%	95.53%	—	—	—	—	—	—
2022	98.74%	96.78%	94.09%	—	—	—	—	—	—
2023	98.43%	95.99%	92.67%	—	—	—	—	—	—
2024	98.12%	95.21%	91.27%	—	—	—	—	—	—
2025	97.81%	94.43%	89.89%	—	—	—	—	—	—
2026	97.50%	93.66%	88.53%	—	—	—	—	—	—
2027	97.19%	92.90%	87.19%	—	—	—	—	—	—
2028	96.88%	92.14%	85.87%	—	—	—	—	—	—
2029	96.58%	91.39%	84.57%	—	—	—	—	—	—

2030	96.27%	90.65%	83.30%	—	—	—	—	—	—
2031	95.15%	89.29%	81.94%	—	—	—	—	—	—
2032	94.04%	87.96%	80.61%	—	—	—	—	—	—
2033	92.95%	86.65%	79.30%	—	—	—	—	—	—
2034	91.86%	85.35%	78.01%	—	—	—	—	—	—
2035	90.79%	84.08%	76.74%	—	—	—	—	—	—
2036	89.73%	82.82%	75.49%	—	—	—	—	—	—
2037	88.69%	81.58%	74.26%	—	—	—	—	—	—
2038	87.66%	80.36%	73.06%	—	—	—	—	—	—
2039	86.63%	79.16%	71.87%	—	—	—	—	—	—
2040	85.62%	77.98%	70.70%	81.34%	70.18%	60.10%	—	—	—
2041	84.93%	77.38%	70.21%	80.68%	69.65%	59.32%	—	—	—
2042	84.23%	76.80%	69.72%	80.02%	69.12%	58.55%	—	—	—
2043	83.54%	76.21%	69.23%	79.37%	68.59%	57.79%	—	—	—
2044	82.86%	75.63%	68.75%	78.72%	68.07%	57.04%	—	—	—
2045	82.19%	75.06%	68.27%	78.08%	67.55%	56.30%	—	—	—
2046	81.51%	74.48%	67.80%	77.44%	67.04%	55.57%	—	—	—
2047	80.85%	73.92%	67.32%	76.81%	66.53%	54.85%	—	—	—
2048	80.19%	73.36%	66.86%	76.18%	66.02%	54.14%	—	—	—
2049	79.53%	72.80%	66.39%	75.56%	65.52%	53.44%	—	—	—
2050	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2051	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2052	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2053	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2054	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2055	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2056	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%

2057	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2058	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2059	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2060	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2061	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2062	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2063	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2064	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2065	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2066	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2067	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2068	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2069	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%
2070	78.89%	72.24%	65.93%	74.94%	65.02%	52.74%	110.4%	72.24%	59.34%

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