# Far-Term Exploration of Advanced Single-Aisle Subsonic Transport Aircraft Concepts

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**Far-term single-aisle class aircraft concepts for potential entry-into-service of 2045 were investigated using an Interactive Reconfigurable Matrix of Alternatives (IRMA) approach. The configurations identified through this design space exploration were then distilled into three advanced aircraft concepts best characterizing the prominent features identified through the IRMA exploration. These three aircraft concepts were then configured and sized for a 150-passenger capacity and a 3,500 nautical mile design mission. Mission block fuel burn was estimated and compared to a far-term conventional configuration baseline concept and a 2005 best-in-class aircraft model. These comparisons suggest considerable potential improvements in fuel efficiency from the investigated advanced concepts.**

## I. Introduction

NASA has been exploring advanced technology subsonic transport aircraft concepts for a number of years, as demonstrated by the significant investments in such efforts under the Environmentally Responsible Aviation (ERA) Project, the Advanced Air Transport Technology (AATT) Project, and its precursors. The Aeronautics Research Mission Directorate (ARMD) continues to put considerable emphasis on performance goals for several generations of aircraft past the state-of-the-art (SOA). Table 1 shows the performance goals listed in the current ARMD Strategic Implementation Plan (SIP) [1]. The NASA N+3 studies completed in the early 2000s laid the groundwork for a suite of N+3 advanced aircraft concepts that garnered significant national and international attention and helped to spur numerous follow on studies [2–6]. Aircraft concepts such as the double-bubble D8 [7] and the truss-braced wing (TBW) [8] garnered considerably more interest in the years since these earlier investigations, resulting in several follow on studies, experiments, and potential future flight testing.

Although NASA has put considerable investment into exploring potential near-term (N+1) and mid-term (N+2 and N+3) advanced aircraft concepts, NASA has placed less emphasis on those with further-term applications (N+4 and onward), as marked by the relatively few commissioned studies [9]. Hence, the AATT Project recently supported a preliminary in-house far-term concept exploration (FTCE) study to explore the design space associated with potential far-term single-aisle aircraft concepts. To this end, the FTCE study carried out a brainstorming exercise using formal methods with assessments of potential advanced technologies and informed by future scenarios analysis. The FTCE study subsequently distilled the results of this exploration into a small set of far-term aircraft concepts which were configured, sized, and analyzed for potential mission and vehicle benefits.

This paper is divided into three primary sections detailing the future scenarios analysis, the design space exploration and brainstorming methods, and conceptual design of the selected far-term advanced concepts. Specifically, Section II describes the future scenario analysis performed in support of the design space exploration. Section III discusses the design space exploration and brainstorming methods, and Section IV presents the selected far-term advanced concepts and the far-term reference concept analysis and results. Finally, Section V concludes with a summary and discussion of future work.

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**Table 1 NASA N+3 Goals for Aircraft [1].**

| Technology Benefits | Technology Generations (Technology Readiness Level = 5–6) | | |
| --- | --- | --- | --- |
| | Near-term 2015–2025 | Mid-term 2025–2035 | Far-term Beyond 2035 |
| Noise (cum below Stage 4) | 22–32 db | 32–42 db | 42–52 db |
| LTO $NO_x$ Emissions (below CAEP 6) | 70–75% | 80% | >80% |
| Cruise $NO_x$ Emissions (relative to 2005 best in class) | 65–70% | 80% | >80% |
| Aircraft Fuel/Energy Consumption: (relative to 2005 best in class) | 40–50% | 50–60% | 60–80% |

## II. Future Scenario Analysis

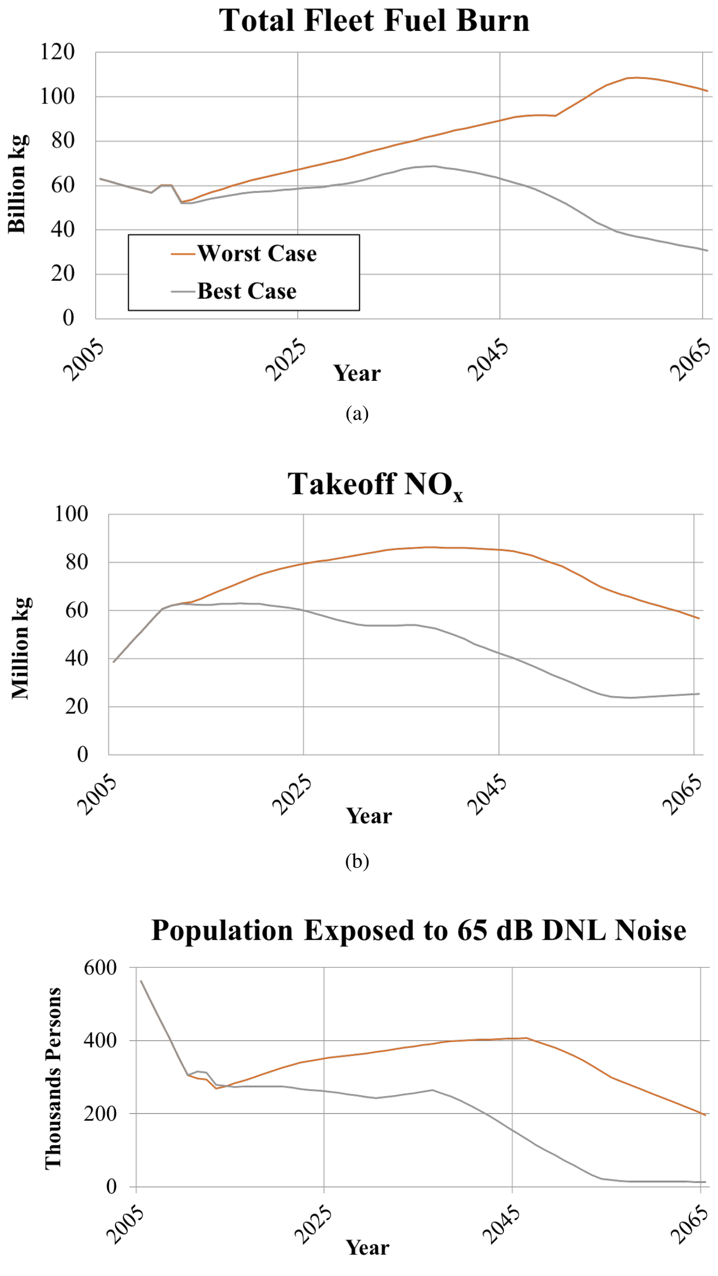
Efficient design space exploration requires the development of a concise, informed set of metrics of interest (MOIs). Accordingly, future scenario analysis for the 2045 timeframe was performed to better understand the relevant fleet-level objectives and assessments applicable to the single-aisle transport class. After surveying the available scenario analysis tools and studies of interest, the Technology Portfolio Assessment and Decision Support (TPADS) portfolio assessment tool was selected [10]. With TPADS, one can readily model the fleet-level impacts of advanced technology packages, variable demand forecasts, and fleet penetration rates for future scenarios up to the N+3 timeframe (nominal EIS of 2030-2035). For this study, the original TPADS tool was augmented with custom far-term (nominal EIS of 2045-2050) technology considerations.

Far-term fleet impacts were modeled by assuming relative reductions in projected fuel burn, noise levels, and emissions. Specifically, the far-term technology impact on fuel burn was modeled as an 80% reduction from the 2005 baseline value, and the far-term technology impact on noise was modeled as a 10 dB reduction in Day-Night Average Sound Level (DNL) from the N+3 model predictions. For the emissions, no change in $NO_x$ was assumed based on the sensitivities noted in the near and mid-term analysis predictions.

The modified TPADS tool was used to model the United States (US) fleet-level fuel burn, takeoff $NO_x$, and number of persons impacted by noise higher than 65 dB DNL through the year 2065, and these properties were computed as a function of technology level, fleet penetration rates, demand forecast model, and vehicle class. Aggregate fleet-level sensitivities for these metrics were estimated by filtering the results for the *best* and *worst case* data as a function of EIS year. These bounding estimates are plotted for total fuel burn, takeoff $NO_x$, and number of population exposed to 65 dB DNL noise levels in Fig. 1. Overall, compared to present-day, significant opportunity for improvements in all three metrics exists in the far-term, with fuel burn possibly offering more opportunity for reduction than $NO_x$ and noise exposure. Further, inspecting the slopes for each of the best and worst case curves for the three metrics at 2045 and onward suggests that fuel burn may pose more challenges to continued improvement in the far-term. Specifically, the worst case fuel burn curve largely continues an upward trend past 2045, despite the application of all technology levels. Hence, these results suggest that fuel burn reductions should remain a focus of vehicle design and analysis studies for far-term applications. It should also be noted that since electric aircraft propulsion (EAP) technologies have not been considered in these fleet assessments, fuel burn as a metric for fleet-level improvement may take on another form as electricity is incorporated into advanced aircraft configurations (such as energy expenditure or total energy cost metrics).

## III. Design Space Exploration

A primary objective of this study was to develop and apply a rigorous method for exploring the complex design space associated with advanced single-aisle aircraft configurations for EIS of 2045 in order to identify novel far-term advanced concepts for further investigation. Accordingly, a survey of available brainstorming methodologies was



(a)

(b)

(c)

**Fig. 1 Best and worst case fleet-level future scenarios for: (*a*) total fuel burn in billion kg; (*b*) takeoff $NO_x$ in million kg; and (*c*) thousands of persons exposed to 65 dB DNL noise for 55 airports across the US.**

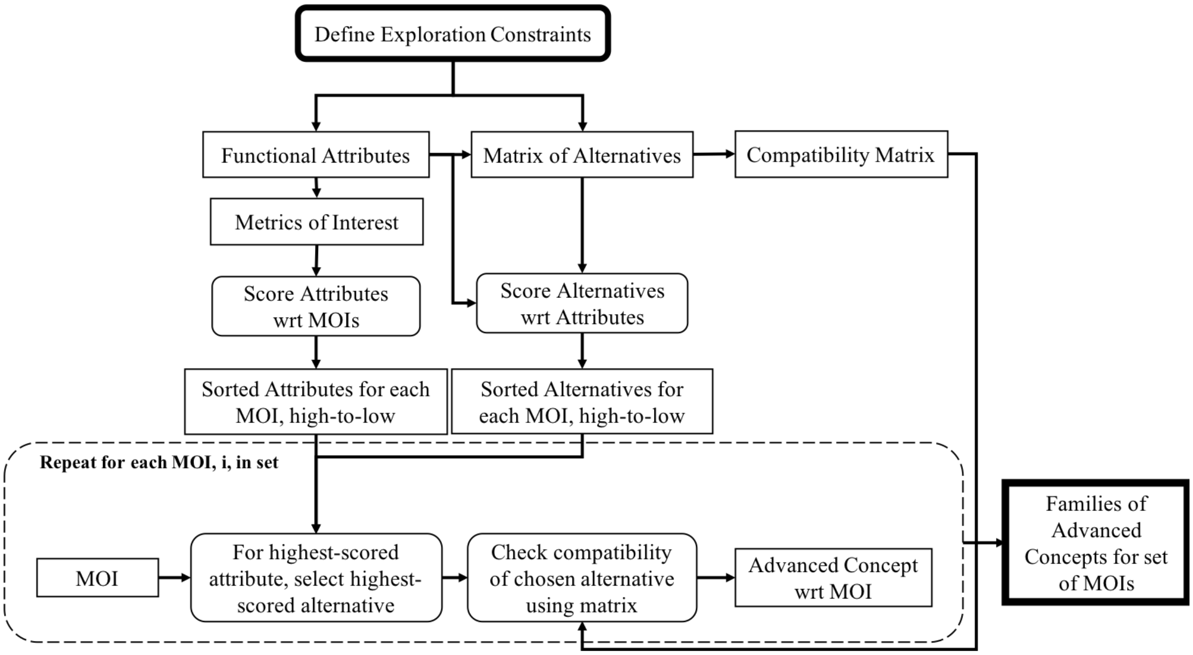


**Fig. 2 Flowchart describing the IRMA brainstorming process used to investigate the design space for far-term single-aisle advanced aircraft concepts.**

conducted, and the Interactive Reconfigurable Matrix of Alternatives (IRMA) methodology was selected to carry out this study [11]. The IRMA toolset developed to support this study is presented in Section III.A, and the accompanying brainstorming results are discussed in Section III.B.

### A. IRMA Methodology

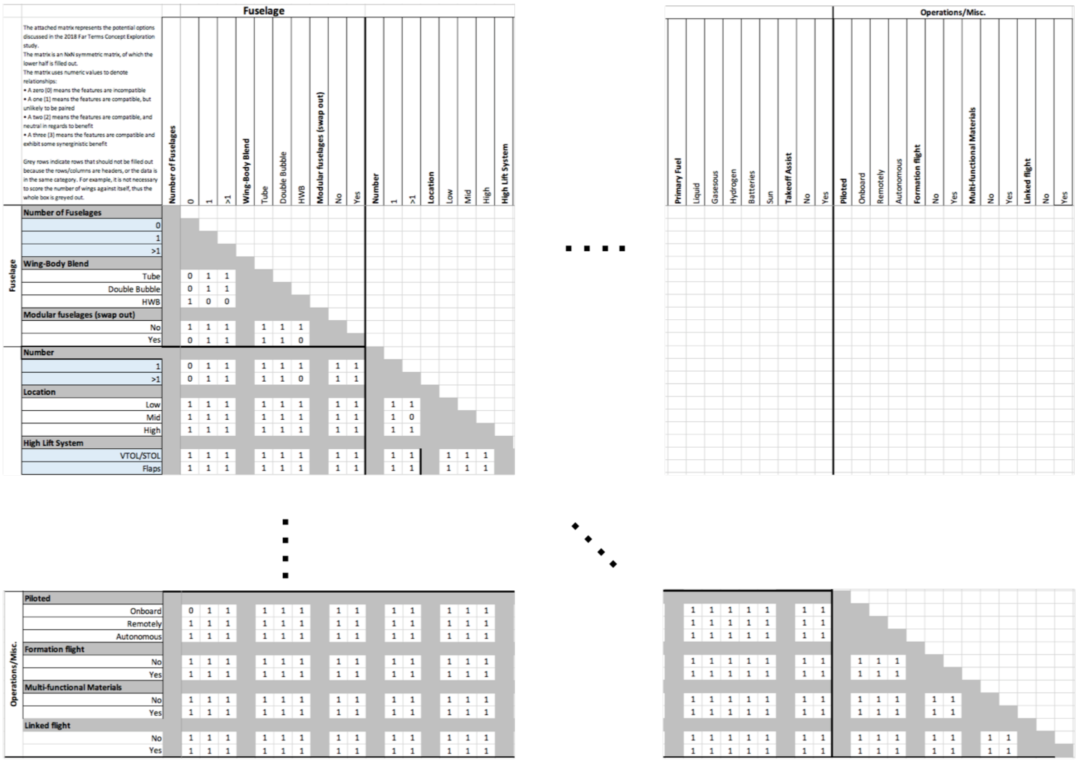
The IRMA methodology was chosen to explore the concept design space due to its rigorous formulation, well-documented development, and repeatability. This method relies on several fundamental components, which interact to provide a brainstorming capability that combines morphological analysis with expert-scored weightings for functional attributes and MOIs. Once a functional taxonomy of the target concept is constructed (i.e. a single-aisle aircraft), the matrix of alternatives (MOA) can be populated with all the relevant alternative attributes for each of the concept functionalities. Next, the MOA developers must build a functional alternative compatibility matrix, which is an N x N, symmetric matrix that describes the compatibility of each attribute alternative with respect to every other attribute alternative. Then, the designers must devise a closed-form set of MOIs, which serves to identify the *corners* of the design space that can be used to focus the exploration effort. With expert scorings of the functional alternatives with respect to the MOIs, expert scorings of the functional alternatives with respect to the functional attributes, and the functional alternatives compatibility matrix constructed, the designers are then able to execute the IRMA brainstorming process as depicted in the flowchart in Fig. 2.

The functional taxonomy proposed by Boeing in early advanced concept studies [5, 9] guided the initial development of the current MOA, shown in Fig. 3. Each of the alternatives shown in Fig. 3 were assessed for compatibility against every other alternative and were compiled into the compatibility matrix depicted in Fig. 4. This compatibility matrix consisted of approximately 9,000 individually ranked pairings, and compatibility was designated as either a 0 for *not compatible* or a 1 for *compatible fully or with contingencies*. This matrix was used to filter out incompatible combinations of the functional alternatives when executing the IRMA brainstorming exercise.

Candidate MOIs were explored as a means of capturing the relevant measures of system-level improvement and design quality. Four MOIs were selected: harmful emissions–including undesirable emissions such as $NO_x$ and $CO_2$; energy consumption–including fuel burn and electricity use; noise–including takeoff and approach; and technology maturation risk–i.e. measure of the risk associated with developing selected technologies to the requisite technology readiness level (TRL) for the target EIS date. Each of the functional attributes was then assigned a score with respect to each MOI representing the level to which each attribute may impact each MOI. These 112 individual numerical scores

| Matrix of Alternatives | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Fuselage** | **Number of Fuselages** | 0 | 1 | >1 | | | | | | |
| | **Wing-Body Blend** | Double bubble | Tube | HWB | | | | | | |
| | **Modular fuselages (swap out)** | Yes | No | | | | | | | |
| **Wing** | **Number** | 0 | 1 | >1 | | | | | | |
| | **Location** | High | Mid | Low | | | | | | |
| | **High Lift System** | VTOL/STOL Config | Flaps | Slats | Circulation Control | Vortex Generators | Vectored thrust | | | |
| | **Bracing** | None | Yes | | | | | | | |
| | **Join** | None | Yes | | | | | | | |
| | **Folding** | None | Telescoping | Swing | Carrier fold | | | | | |
| | **Morphing** | None | Yes--could mean a lot | | | | | | | |
| | **Winglet** | None | Yes | | | | | | | |
| | **Modular** | None | Yes | | | | | | | |
| | **Laminar Flow** | None | Partial | Full | | | | | | |
| **S&C** | **Pitch Effecter** | Conventional horizontal tail | T-Tail | V-Tail | Canard | Wing TE | Active structural stiffening | Vectored thrust | CG tavel | |
| | **Yaw Effecter** | Conventional vertical tail | V-tail | H-tail | winglet | Differential thrust | Active structural stiffening | Vectored thrust | CG travel | |
| | **Roll Effecter** | Conventional ailerons | Wing warping | Active structural stiffening | Vectored thrust | CG travel | | | | |
| **Propulsor Integration** | **Location** | Under wing | Above wing | Embedded in wing | Aft fuselage | Mid fuselage | Embedded in fuselage | Empennage | Wing tips | Midwingspan |
| | **Propulsor Type** | Prop | Open rotor | HBPR fan | UHBPR fan | Body fan/TCT | BLI engine | | | |
| | **Number** | 1 | 2 | >2 | | | | | | |
| | **Propulsor Arrangement** | Discrete | Distributed | | | | | | | |
| | **Energy Conversion** | Brayton | Const V | Fuel cell | IC/piston | Electric motor | Solar | | | |
| | **Augmentation** | None | Battery | Fuel cell | Brayton | Solar | | | | |
| | **Primary Fuel** | Liquid | Gasesous | Hydrogen | Batteries | Sun | | | | |
| | **Takeoff Assist** | No | Yes | | | | | | | |
| **Operations/Misc.** | **Piloted** | Onboard | Remotely | Autonomous | | | | | | |
| | **Formation flight** | Yes | No | | | | | | | |
| | **Multi-functional Materials** | Yes | No | | | | | | | |
| | **Linked flight** | Yes | No | | | | | | | |

**Fig. 3 Matrix of alternatives used for the far-term concept exploration IRMA brainstorming.**



The attached matrix represents the potential options discussed in the 2018 Far Terms Concept Exploration study.

The matrix is an NxN symmetric matrix, of which the lower half is filled out.

The matrix uses numeric values to denote relationships:

- A zero (0) means the features are incompatible
- A one (1) means the features are compatible, but unlikely to be paired
- A two (2) means the features are compatible, and neutral in regards to benefit
- A three (3) means the features are compatible and exhibit some synerginistic benefit

Grey rows indicate rows that should not be filled out because the rows/columns are headers, or the data is in the same category. For example, it is not necessary to score the number of wings against itself, thus the whole box is greyed out.

**Fig. 4 Matrix detailing the functional alternatives compatibilities with respect to each other alternative. Due to its large dimensions, a truncated form of the matrix is shown here.**

|  | MOI--> | Harmful Emissions |  |  |
|---|---|---|---|---|
| **Function** | **Attribute** | **Alternative 1** | **Alternative 2** | **Alternative 3** |
| **Fuselage** | **Number of Fuselages** | 0 | 1 | 1 |
|  | **Wing-Body Blend** | HWB | Tube | DB |
|  | **Modular fuselages (swap out)** | No | No | No |
| **Wing** | **Number** | 1 | 1 | 1 |
|  | **Location** | Low/Mid | High | Low |
|  | **High Lift System** | Flaps | Vectored Thrust | Flaps |
|  | **Bracing** | No | Yes | No |
|  | **Join** | No | No | No |
|  | **Folding** | Telescoping | Telescoping | No |
|  | **Morphing** | Yes | No | No |
|  | **Winglet** | Yes | Yes | Yes |
|  | **Modular** | No | No | No |
|  | **Laminar Flow** | Yes | Yes | Yes |
| **S&C** | **Pitch Effecter** | Wing TE | Flaps | Conventional |
|  | **Yaw Effecter** | Winglet | Winglet | H-Tail |
|  | **Roll Effecter** | Wing Warping | Ailerons | Ailerons |
| **Propulsor Integration** | **Location** | Above Wing - Rear | Under Wing | Above Fuselage-Rear |
|  | **Propulsor Type** | BLI UHBPR Fan | Open Rotor | BLI HBPR Fan |
|  | **Number** | 3 | 2 | 2 |
|  | **Propulsor Arrangement** | Discrete | Discrete | Discrete |
|  | **Energy Conversion** | Const V/Motor | Const V/Motor | Fuel Cell/Motor |
|  | **Augmentation** | Battery | Battery | Battery |
|  | **Primary Fuel** | Liquid | Liquid | Hydrogen |
|  | **Takeoff Assist** | Yes | Yes | Yes |
| **Operations/Misc.** | **Piloted** | Remotely | Remotely | Remotely |
|  | **Formation flight** | No | No | No |
|  | **Multi-functional Materials** | Yes | No | Yes |
|  | **Linked flight** | No | No | No |

**Fig. 5 An example of three concept families identified through the IRMA exploration for the harmful emissions MOI.**

took on values from 0 to 3, where 0 represented *least impactful* and 3 represented *most impactful*. Next, each of the functional attribute alternatives in the MOA was scored with respect to each MOI representing the relative benefit each alternative may impart on each MOI; these 416 individual scores took on values from 0 to 10, where 0 represented *most negative benefit* and 10 represented *most positive benefit*.

After the relevant scorings were completed, families of candidate advanced concepts were brainstormed by methodically selecting highest- to lowest-ranked alternatives for the highest- to lowest-scored attributes for each of the MOIs, as shown within the dashed box in Fig. 2. A check on alternatives compatibility with the compatibility matrix was performed at each selection of an alternative. Due to a subset of the alternatives being scored equally, the brainstormers were required to exercise engineering judgement in order to arrive at each single family of advanced concepts, which was defined as a closed set of alternative selections for all the functional attributes.

## B. Results

For each of the four MOIs, three possible concept families were identified using the IRMA approach described in Fig. 2, resulting in a total of approximately twelve families of potential advanced concepts characterizing the chosen design space. One such example of a brainstormed concept family is shown in Fig. 5, where three concept families defined through the IRMA brainstorming process are shown for the harmful emissions MOI. For each of the MOIs, identifying the candidate concept families required striking a balance between following the algorithmic IRMA approach detailed in Fig. 2 and manually perturbing the alternatives selection process in order to arrive at concepts that were predominantly exclusive of one another, while also minimizing redundant design features and maximizing the opportunity for worthwhile vehicle analysis.

For each of the concept families identified through the IRMA exploration, the authors configured a single aircraft geometry model. A collection of many of these potential far-term aircraft configurations is shown in Fig. 6. One can see in these concepts the wide variation in configuration designs, spanning what may be considered conventional planforms to what may be considered very advanced configurations. Many of these concepts leverage unconventional means of achieving stability and control, such as actuated winglets, vectored thrust, and canards. Additionally, many of these concepts attempt to leverage potential EAP technologies for more advanced propulsion-airframe integration approaches

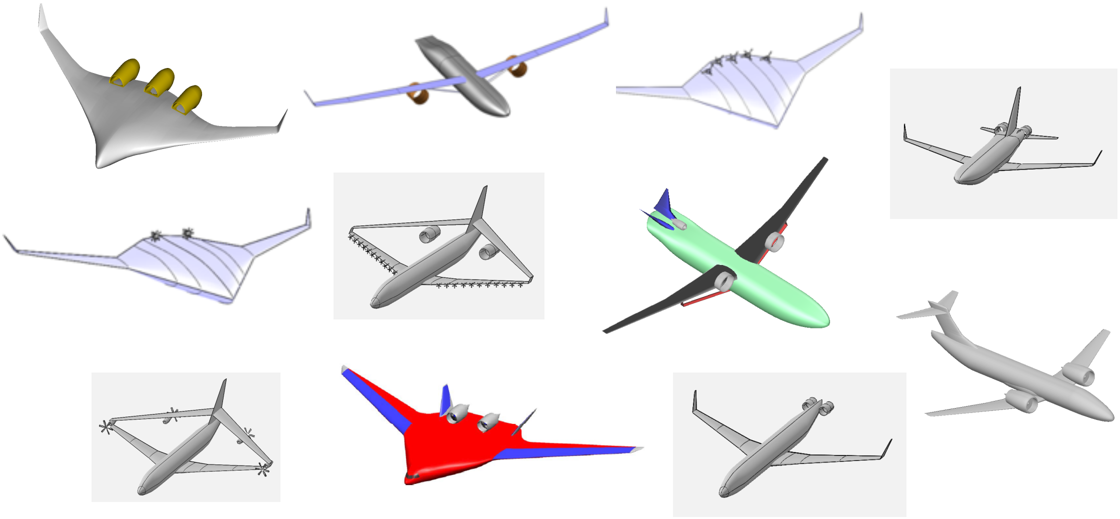


**Fig. 6 A visual depiction of some of the far-term concept families created using the IRMA brainstorming approach.**

and energy consumption reductions. Finally, one can also see in this set of far-term concepts several similar to those studied in the earlier N+3 studies, which is to be expected as the IRMA toolset was in part informed by this earlier work.

## IV. Advanced Concept Analysis

After completing the IRMA brainstorming exploration, a concerted effort was made to distill the swath of IRMA advanced concepts into a small set of far-term advanced concepts to be studied for potential mission-level benefits. After poring over the families of advanced concepts in the IRMA results, several observations of recurrent design features were made. First, many of the concepts tended toward removing the empennage, which encompasses the aft horizontal and vertical stabilizers in a traditional configuration, in favor of more unconventional, forward-positioned lifting surfaces to maintain control authority with the benefit of significant reductions in wetted area. Second, the concepts tended toward leveraging ultra high bypass ratio (UHBPR) turbofans on account of their favorable scoring for fuel efficiency and emissions. A tendency toward lifting fuselage bodies, either in the form of a hybrid-wing-body (HWB) or in the form of double-bubble-inspired fuselage configurations, was apparent, which aimed to leverage synergistic fuselage-wing interactions. Finally, EAP architectures were frequently selected due to the numerous potential integration, efficiency, and emissions benefits.

With the observations above, the authors set out to configure three far-term advanced aircraft concepts that were *most* representative of the wider families of concepts identified through the IRMA exercise. To this end, a Far-Term HWB (FTHWB) concept, a Far-Term Truss-Braced Wing (FTTBW) concept, and a Far-Term Tailless Airliner (FTTA) concept were configured for detailed conceptual design and analysis. Additionally, in order to make fair and informative performance assessments, a Far-Term Reference Concept (FTRC) characterized by EIS 2045 advanced technologies and a conventional configuration was modeled. The FTRC model is presented in Section IV.A, along with a discussion of general design assumptions and a description of the design mission. The FTHWB, FTTBW, and FTTA concepts are presented in Sections IV.B, IV.C, and IV.D, respectively, and mission performance results are discussed in Section IV.E.

### A. Far-Term Reference Concept

The FTRC conventional configuration baseline vehicle was developed from an earlier N+3 advanced technology baseline vehicle, commonly referred to as the N+3 Conventional Configuration (N3CC) [12]. A three-view illustration of the FTRC is shown in Fig. 7, for reference, as modeled using Open Vehicle Sketch Pad (OpenVSP) [13]. The wing span and fuselage length were fixed at approximately 118 ft and 125 ft, respectively. The configuration was modeled generally after a Boeing 737-800, but augmented with far-term (N+4) technology assumptions.

Mission analysis and vehicle sizing were performed using the FLight Optimization System (FLOPS) [14] according to the mission profile described in Fig. 8. The design mission was modeled to approximate the Boeing Refined SUGAR

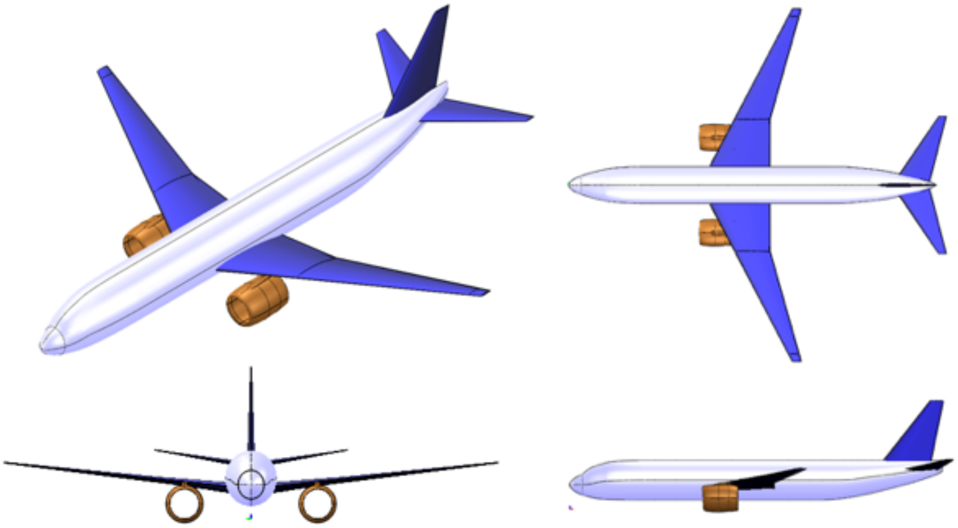


Fig. 7 A three-view illustration of the Far-Term Reference Concept.

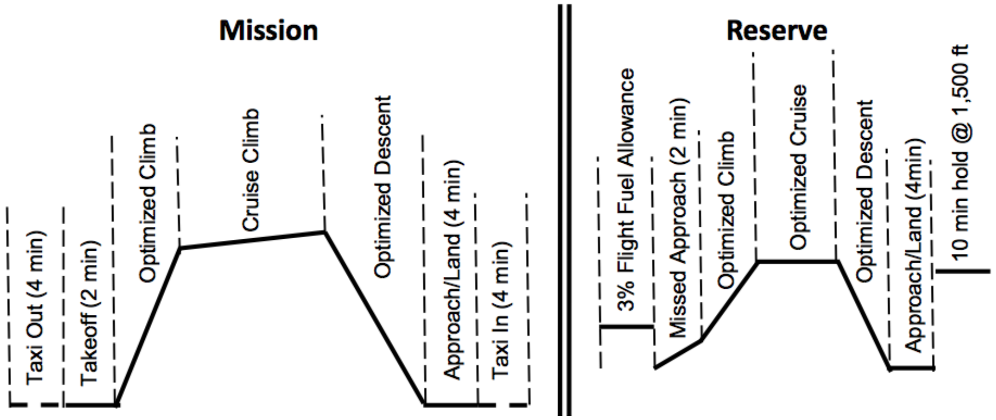


Fig. 8 Design mission modeled in FLOPS for sizing the FTRC and the far-term advanced concepts [12].

N+3 mission profile [5], and a detailed discussion of this mission profile is available in Ref. [12]. The mission profile included an optimized climb segment unconstrained by airspeed, a cruise climb segment at optimal altitude for specific range, and an optimized descent. The cruise Mach number was fixed at 0.785, and the design range was set to 3,500 nm. An economic (econ) mission range of 900 nm was also analyzed.

The technology assumptions made for the FTRC, in comparison to the N3CC, were largely informed by the Boeing SUGAR N+4 study [9]. Specifically, these assumptions included: adding natural laminar flow (NLF) benefits to the nacelles and tail via enhanced transition delay, in addition to the NLF benefit assumed for the wing in the N3CC model; drag buildup calibration based on the Boeing N+4 Refined SUGAR model; calibration of the NASA N+3 UHBPR geared turbofan engine [15] to match fuel flow rate of the gFan++ engine [16]; and minimal improvements in structural properties over the N+3 technology assumptions.

Sizing and performance results for the FTRC are summarized in Table 2, where comparisons to the NASA N3CC and the Boeing N+4 Refined SUGAR concepts are made. Comparing the results of the FTRC to those of the N3CC suggests modest improvements aerodynamically, as demonstrated by increased L/D, and propulsively, as demonstrated by reductions in propulsion system weight and top-of-climb (TOC) TSFC. These improvements, combined with reduced operating empty weight (OEW), result in vehicle block fuel burn reductions of 14% for the design mission and 13% for the economic mission.

**Table 2 Summary of Far-Term Reference Concept Sizing and Performance Results Compared to the N3CC and Boeing N+4 Refined SUGAR Concepts**

| Parameter | NASA N3CC | Boeing N+4 Refined SUGAR | NASA FTRC |
|---|---|---|---|
| Cruise Mach | 0.785 | 0.74 | 0.785 |
| TOGW (lb) | 141,000 | 136,400 | 134,600 |
| OEW (lb) | 83,000 | 79,210 | 74,990 |
| Engine Weight (lb) | 7,150 | 9,280 | 6,490 |
| L/D, start of cruise | 20.7 | 22.7 | 22.0 |
| SLS Thrust (lb) | 25,000 | 21,940 | 22,000 |
| TSFC, top of climb | 0.470 | 0.453 | 0.456 |
| TSFC, cruise | 0.455 | 0.453 | 0.459 |
| Design Block Fuel Burn (lb) | 24,150 | Not Reported | 21,190 |
| Econ Block Fuel Burn (lb) | 6,680 | Not Reported | 5,920 |

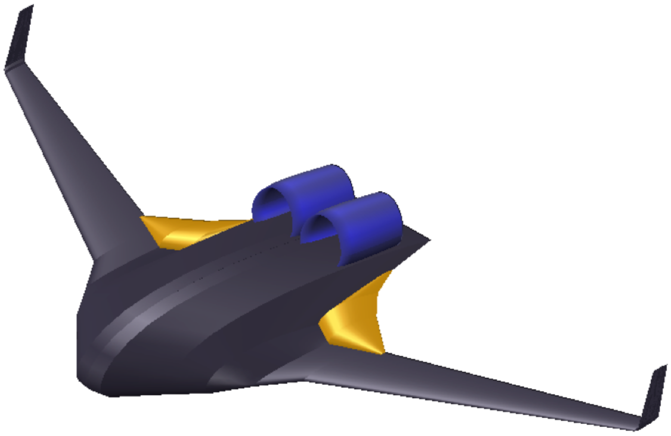


**Fig. 9 An isometric view of the Far Term Hybrid Wing Body Concept.**

### B. Far-Term Hybrid Wing Body Concept

The FTHWB is a far-term advanced concept designed to reduce fuel consumption, emissions, and noise propagation predominantly through the use of an advanced HWB planform with a modular hybrid-electric propulsion architecture. Specifically, this concept is marked by a high aspect ratio wing, a non-circular fuselage section, integrated UHBPR geared turbofans, a continuous trailing edge with oversized winglets, and a parallel hybrid-electric propulsion architecture with modular battery assemblies to provide power assist for takeoff and climb. An isometric view of the FTHWB concept is shown in Fig. 9, where the yellow bodies represent deployable battery packs that can be released and safely returned to the ground for recovery once the onboard battery power is exhausted at TOC.

The outer moldline (OML) was modeled starting with the NASA N2A [17] and subsequently resized and reshaped for the targeted 150 passenger payload, including an additional four crew and associated cargo. The wing span and fuselage length were 158 ft and 75 ft, respectively–representing a significant increase in wing span over the FTRC. The passenger cabin is approximately 20 ft by 40 ft and is marked by two 20 in aisles with a three by four by three abreast seating arrangement. Given the integrated UHBPR turbofans on the aft section of the aircraft, little room was available for vertical tails. Hence, oversized winglets were added for yaw authority, and the rear trailing edge of the OML is assumed to be continuously actuated via distributed elevons. Previous studies have indicated that such an arrangement may offer substantial savings in actuation power for maneuvering [18]. While the integrated engines may support application of boundary-layer-ingestion (BLI) technologies, no such benefits were assumed for this configuration. Additionally, the internal structure was assumed to be comprised of the PERSEUS material concept [19], which offers substantial weight savings for non-circular pressurized HWB structures [20].

Given the unfavorable weight scaling of batteries and the high efficiency of electric propulsion, the parallel hybrid-electric architecture onboard the FTHWB is used to supply supplemental power nominally through TOC, at which point the depleted batteries are jettisoned. In this way, the chief effect of the onboard battery power is to reduce the effective fuel consumption required by the integrated UHBPR turbofans to meet required thrust demands. Companies are becoming increasingly interested in electric-assist turbofan concepts [21, 22], and the detailed design of such a system was beyond the scope of this work. Rather, the effect that such a system may have on the sizing of a single-aisle class advanced concept was the primary focus.

FLOPS was used to size the aircraft for a 3,500 nm design range using the same mission profile segments and sizing constraints applied to the FTRC. Due to the unique modular parallel hybrid-electric architecture, special considerations were made to account for the battery weight and electrical motor weight required to supply the electric power to the UHBPR turbofans. Due to limitations imposed by the architecture of FLOPS, the batteries and electric motors were sized outside of FLOPS, but the results of the sizing were iterated with the FLOPS analysis to ensure a closed design. Specifically, a routine was developed to estimate the energy consumed as a function of time using the FLOPS mission analysis results. By then assuming a target power extraction ratio (i.e., the amount of power supplied by onboard batteries versus supplied by onboard combustible fuel) and battery and electric motor technology levels, one can readily calculate the electric motor and onboard battery weights required to supply the targeted electric power level through the targeted mission segments. For this study, battery specific energy and electric motor specific power were assumed to be 1,150 Wh/kg and 28 kW/kg, respectively, based on extrapolating projections published at the 2018 Electric and Hybrid Aerospace Technology Symposium [23] to the 2045 timeframe. Weights for other electrical components were not explicitly modeled for this study; rather, a scaling factor was applied to the predicted battery and electric motor weights. In order to simulate the deployment of the battery packs at TOC, all weight associated with the batteries was modeled in FLOPS as cargo weight. Mission performance results are described below in Section IV.E.

### C. Far-Term Truss-Braced Wing Concept

The FTTBW is a far-term advanced concept that leverages a TBW configuration with the addition of a morphing wing and an electrically driven BLI tailcone thruster (TCT). An isometric view of the FTTBW concept is shown in Fig. 10. Integration of the TCT into the rear of the fuselage is facilitated through the removal of the conventional horizontal stabilizer. Instead, a lifting canard is installed at the front of the aircraft for pitch authority. A morphing wing, which allows the wingtips to fold vertically during low speed flight for added yaw authority, reduced the wetted area of the vertical stabilizer. The electricity for the TCT is generated through a combination of onboard batteries and generators integrated into under-wing-mounted turbofans, resulting in a series/parallel hybrid-electric propulsion system.

The FTTBW concept was designed for a Mach 0.785 cruise condition and was sized according to the FTRC mission requirements and profile described previously. Design and sizing of the FTTBW concept leveraged the TTBW FLOPS model developed previously by Wells [24]. The initial geometry of the wing was similar to that developed under a recent NASA-funded NRA with Boeing [25], and the wing span and fuselage length were 146 ft and 127 ft, respectively. The aerodynamic drag was also calibrated using the results of the same study, in which a similar far-term TTBW concept was designed that utilized an alternative hybrid-electric propulsion architecture. The FLOPS wing weight predictions were made utilizing wing weight correction factors from previously funded studies [26]; all other structural weights were computed using the uncorrected FLOPS equations. The addition of the lifting canard reduced the area of the main wing and also decreased the potential installation losses for the TCT by allowing for removal of the horizontal stabilizer. Further, the addition of the folding main wing enables the vertical tail to be reduced in area, potentially as much as 50%, based on extrapolation of flight test data obtained for a spanwise adaptive wing mounted on the Prototype-Technology Evaluation Research Aircraft (PTERA) [27].

The FTRC engine model served as the basis of the propulsion model for the FTTBW and was augmented to reflect the series/parallel hybrid-electric architecture proposed here. Additional propulsion system weights of 1,770 lb and 3,500 lb were applied to account for the addition of the onboard batteries for the series/parallel hybrid-electric architecture and the TCT propulsor, respectively. Additionally, the estimated aeropropulsive benefit of the TCT on the configuration was applied as an effective 4.5% reduction in fuel flow rate. Mission performance results for the FTTBW are discussed in Section IV.E.

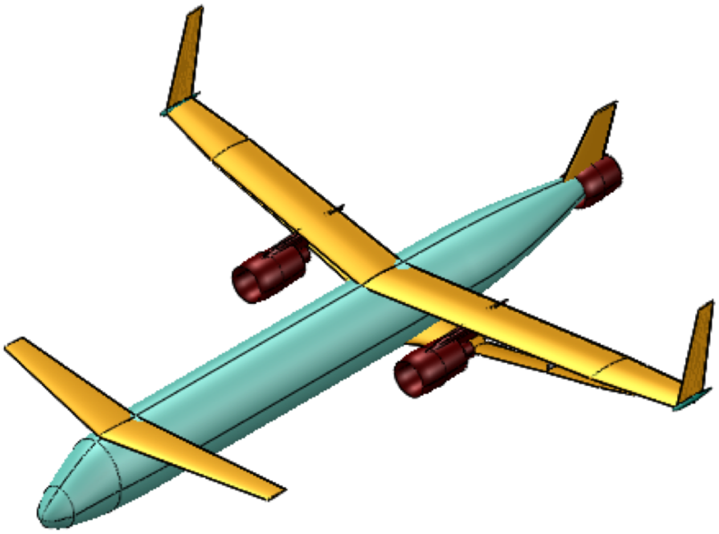


**Fig. 10 An isometric view of the Far Term Truss-Braced Wing Concept.**

### D. Far-Term Tailless Airliner Concept

The FTTA is a far-term advanced concept that leverages a more conventional tube-and-wing layout but is marked by the absence of any conventional tail assembly and the addition of fuselage-mounted UHBPR turbofan engines and wingtip-integrated electric propellers. An isometric view of the FTTA is shown in Fig. 11. This concept was inspired in part by an earlier study by Raymer, et al. [28], in which design sensitivities of a tailless airliner concept were investigated. Electrically driven propulsors are integrated at the wingtips to reduce the induced drag associated with the main wing lift generation and to provide yaw authority. Pitch authority is achieved through the use of a canard. The electricity required to power the wingtip propulsors is produced onboard by generators integrated into the UHBPR turbofans, creating a turboelectric propulsion system architecture. The location of the turbofan engines along the aft fuselage introduces potential noise benefits germane to mid-fuselage nacelle (MFN) vehicle configurations [29].

The FTTA airframe geometry is a modified version of the FTRC, wherein the original empennage was removed, a lifting canard added, and the main wing translated aft. The wing span and fuselage length remain unchanged from that of the FTRC at 118 ft and 125 ft, respectively. The vehicle was sized assuming a cruise Mach of 0.785 and according to the same mission profile described previously for the FTRC, FTHWB, and FTTBW. Structural weight scaling factors were leveraged from the FTRC FLOPS analysis, as well as all aerodynamics modeling parameters except those for induced drag. Specifically, because of the wingtip mounted electric propulsors and the assumed reduction in integration losses, a 10% reduction in total induced drag was assumed for this study.

The FTRC UHBPR geared turbofan propulsion model was leveraged for this configuration and modified for the turboelectric power architecture. The total propulsion system weight was increased by 15% to account for the electrical system components. The wingtip electric propulsors were assumed to weigh approximately 2,000 lb, based on an assumed power split and the same motor specific power described above for the FTHWB. Since the assumed PAI benefit was modeled via a reduced induced drag, these propulsors were applied as point masses in the mission analysis. Mission performance results for the FTTA are discussed in Section IV.E.

### E. Results

Summarized mission performance results for the FTHWB, FTTBW, and FTTA are tabulated in Table 3 adjacent those of the FTRC, and unless explicitly described in Sections IV.B-IV.D above, the advanced concepts leveraged identical mission and vehicle design assumptions to the FTRC. Immediately apparent in Table 3 are the increases in OEW and takeoff gross weight (TOGW) for each of the advanced concepts relative to the FTRC baseline. The reasons for these weight increases vary per concept, but the increases arise largely due to the differences in propulsion system architectures. For example, the FTHWB and FTTBW both rely on hybrid-electric architectures leveraging large onboard batteries, and the FTTA leverages a turboelectric architecture that requires additional electrical motors, generators, and

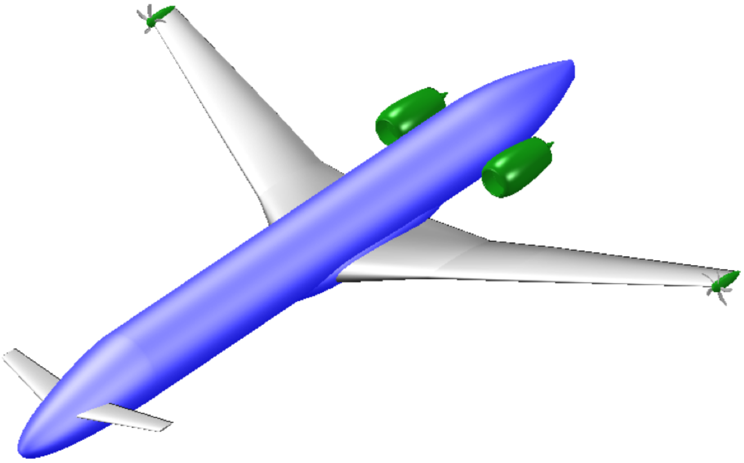


**Fig. 11 An isometric view of the Far Term Tailless Airliner Concept.**

transmission components to be integrated into the configuration. Additionally, some of this added weight is associated with the aerostructural ramifications of the HWB and TTBW configurations, such as the advanced structural concepts required for non-circular pressure vessel for the FTHWB and the truss assemblies and fuselage integration challenges associated with the FTTBW.

Although the advanced concepts are generally heavier and larger than the FTRC, these increased weights are generally accompanied by significant increases in propulsion system and aerodynamic efficiencies. As can be seen in Table 3, all three of the advanced concepts are characterized by significant increases in the ratio of lift-to-drag (L/D), with the FTHWB benefiting most. The FTTBW and FTTA also benefit from effective increases in L/D primarily through reductions in induced drag, but to less of an extent than the FTHWB.

Block fuel burn and TSFC predictions are reported for each of the advanced concepts, which are compared to those of the FTRC. It should be noted that due to the necessarily ad hoc nature of the hybrid-electric propulsion modeling required by FLOPS, comparing the TSFC results for the advanced concepts to those of the FTRC is likely not a sound comparison. Rather, more illustrative comparisons to make are those of block fuel burn for the design and econ missions, for which all three advanced concepts compare favorably to that of the FTRC. Specifically, with increasing departures from the baseline, the FTTA, FTTBW, and FTHWB achieve increasingly greater reductions in block fuel burn for both the 3,500 nm design mission and the 900 nm econ mission.

Percentage reductions in block fuel burn for the design and econ missions are shown in Table 4 for the advanced concepts compared to both the current FTRC baseline as well as the NASA 2005 best-in-class single-aisle baseline, which is based on an aircraft model representative of the Boeing 737-800 [30]. In this table, the magnitude of mission performance improvement for the advanced concepts is apparent. Specifically, the FTHWB, FTTBW, and FTTA achieve up to 26%, 12%, and 9% reductions in design mission block fuel burn as compared to the FTRC, with the FTHWB achieving even greater reductions in block fuel burn for the econ mission because of the electric assist during climb out. When compared to the 2005 best-in-class baseline, the FTHWB, FTTBW, and FTTA analyses suggest potential block fuel burn reductions up to 67%, 61%, and 60%, respectively. Although these benefits will inevitably decrease as analysis assumptions tighten with increasing model fidelity, the current analysis suggests the potential for these advanced concepts to meet the ambitious far-term commercial transport performance goals set out in the NASA ARMD SIP [1].

**Table 3 Summary of FTHWB, FTTBW, and FTTA Sizing and Performance Results Compared to the FTRC**

| Parameter | FTRC | FTHWB | FTTBW | FTTA |
|---|---|---|---|---|
| Cruise Mach | 0.785 | 0.785 | 0.785 | 0.785 |
| TOGW (lb) | 134,550 | 146,597 | 145,102 | 134,797 |
| OEW (lb) | 74,985 | 86,971 | 87,383 | 80,022 |
| Engine Weight (lb) | 6,489 | 7,448 | 6,222 | 8,240 |
| L/D, start of cruise | 22.0 | 32.2 | 27.3 | 24.4 |
| SLS Thrust (lb) | 22,000 | 25,000 | 20,352 | 27,117 |
| TSFC, top of climb | 0.456 | 0.456 | 0.434 | 0.456 |
| TSFC, cruise | 0.459 | 0.482 | 0.441 | 0.463 |
| Design Block Fuel Burn (lb) | 21,192 | 15,739 | 18,567 | 19,311 |
| Econ Block Fuel Burn (lb) | 5,921 | 4,053 | 5,334 | 5,486 |

**Table 4 Summary of Block Fuel Burn Reductions Relative to NASA 2005 Best-in-Class Baseline Boeing 737-800 and NASA FTRC**

| | FTHWB | FTTBW | FTTA |
|---|---|---|---|
| Benefit over FTRC (Design) | 26% | 12% | 9% |
| Benefit over FTRC (Econ) | 32% | 10% | 7% |
| Benefit over 2005 Best-in-Class (Design) | 67% | 61% | 60% |
| Benefit over 2005 Best-in-Class (Econ) | 68% | 58% | 57% |

## V. Summary and Future Work

A structured brainstorming process was used to generate far term single-aisle commercial subsonic transport aircraft concepts, and these conceptual designs were targeted for potential EIS of 2045 and beyond. A fleet projection was performed first to inform the study as to potential market and aircraft performance trends. This analysis suggested a continued emphasis on reductions in fuel burn (or energy consumption) and noise, along with a reduced emphasis on emissions reductions due to the significant progress made through projected near-term and mid-term technology applications. With these insights, a brainstorming framework leveraging the IRMA methodology was used to explore the design space for potential advanced concepts. This exploration required identifying metrics of interest, compiling relevant technologies, performing morphological analysis, developing technology compatibility matrices, and performing IRMA scorings and concept rankings, leading to numerous potential advanced concepts. A down-select exercise yielded three largely orthogonal advanced configurations, including the FTHWB, FTTBW, and FTTA, for further design and mission analysis. A far-term advanced technology conventional configuration baseline vehicle, referred to as the FTRC, was developed to serve as a comparison baseline for the far-term advanced concepts.

Mission performance results from this preliminary investigation suggest considerable potential fuel burn reductions for the FTHWB, FTTBW, and FTTA concepts. For the FTHWB, these benefits are largely a result of the increased aerodynamic efficiency of the blended wing body planform with the oversized winglets and advanced structures concepts, combined with the impact of the modular parallel hybrid-electric propulsion architecture featuring jettisoned batteries. For the FTTBW, the projected fuel burn benefits are largely a result of the increased aerodynamic efficiency of the TBW, combined with the series/parallel hybrid-electric propulsion architecture featuring a TCT designed to minimize integration losses. Finally, for the FTTA, the benefits in fuel burn result primarily from the reductions in total wetted area and reduced induced drag from the removal of the conventional empennage assembly and integration of wingtip mounted propulsors.

Given the preliminary nature of this study, considerable future work is required to reduce the uncertainty associated with the mission performance results. Several gaps in the analysis that were noted during the current study include: properly accounting for one engine inoperative conditions given the modifications to the yaw authority controllers, and considering stability and control more generally; developing custom propulsion architecture models incorporating the hybrid-electric design features and potential BLI benefits; utilizing a metric for assessing concept benefits that fairly considers energy type and production costs; aerostructural design and analysis of the modular battery banks; and higher-fidelity investigations into the potential induced drag reductions of wingtip mounted propulsors.

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