Far Term Noise Reduction Roadmap for the NASA D8 and Single-Aisle Tube-and-Wing Aircraft Concepts

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A portfolio of noise reduction technologies is applied to two advanced single-aisle class vehicle concepts in order to evaluate the prospects for these aircraft to meet the NASA Far Term noise goals, beyond 2035. The NASA D8 (ND8) aircraft is an unconventional configuration with boundary-layer ingesting engines mounted in the aft dorsal location. The 160-passenger tube-and-wing (TW160) aircraft is a conventional configuration with podded engines located under the wing, which represents an incremental evolution of current design philosophies. The noise reduction technologies were chosen to be compatible with each aircraft's specific configuration requirements. The acoustic effects were predicted based on experimental and numerical studies, and were incorporated into the prediction of total system noise using NASA's research-level Aircraft NOise Prediction Program (ANOPP-Research). Results suggest that the unfavorable Propulsion Airframe Aeroacoustic (PAA) effects of the two aircraft considered here significantly limit their prospects of meeting NASA's Far Term noise goal, and that further development of the technology portfolio is key to ensuring future success in addressing the noise challenges for single-aisle class vehicles.

I. Introduction

To assess the feasible noise performance of future NASA aircraft concepts in the Far Term time frame, two studies have been published previously wherein advanced noise reduction technologies were applied to the Hybrid Wing Body (HWB) [1] and Mid-Fuselage Nacelle (MFN) [2] aircraft. The studies have shown that the noise reduction technologies, together with the noise shielding and advanced design features of the two configurations, allow the HWB and MFN to reach Effective Perceived Noise Levels (EPNL) that are 50.9 dB and 40.2 dB, respectively, below the cumulative certification regulation of Stage 4 defined in the Code of Federal Regulations (CFR) Title 14, Chapter 1, Part 36 [3]. These previous studies have focused on aircraft in the 301-passenger class. However, the majority of the in-service commercial transport fleet is currently comprised of smaller single-aisle aircraft in the 160- to 220-passenger range. These smaller aircraft can have very different noise characteristics compared to larger twin-aisle aircraft. As an example, the HWB and MFN aircraft feature six-wheel main landing gear, the size and complexity of which make the main landing gear a prominent noise source during final approach. Smaller single-aisle aircraft feature two-wheel main gear, and because of its much simpler architecture, the noise from the main landing gear may be less important relative to those of the high-lift system and engines. As such, noise reduction technologies such as the pod gear concept explored in previous studies [1, 2, 4] will have different impacts on the overall system level noise, as noise source rankings change with overall aircraft size. It is therefore necessary and worthwhile to conduct a similar Far Term noise reduction roadmap for smaller aircraft, both to evaluate the effectiveness of noise reduction technologies on these aircraft, as well as to guide future development of the Far Term technology portfolio that is likely to have the greatest impact on fleet-level noise metrics.

In this study, the two advanced concepts shown in Figure 1 are identified as aircraft with characteristics that could, in the future, be incorporated into the single-aisle fleet that is currently dominated by the Boeing 737 and Airbus A320. The first is the 180-passenger NASA D8 concept that is based on the Massachusetts Institute of Technology (MIT)/Aurora Flight Sciences D8 aircraft first developed under a 2008 NASA Research Announcement [5] and later updated by Drela [6]. Yutko et al. [7] undertook a comprehensive conceptual design of the MIT/Aurora D8. The NASA

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Advanced Air Transport Technology (AATT) project has independently evaluated the D8 concept for several years [8, 9]. The designation NASA D8 (ND8) was developed to differentiate the NASA model of the D8 from the MIT/Aurora D8 model, since different tools and assumptions were used to develop the models. The ND8 is designed to resemble the overall D8 concept with details provided by NASA tools and models for aircraft design, analysis, and optimization, using 2035 as the expected entry-into-service date.

The second concept considered here is the 160-passenger tube-and-wing (TW160) aircraft concept that was originally developed under the NASA Environmentally Responsible Aviation (ERA) Project. This aircraft is designed using NASA tools and assumptions for a 2025 entry-into-service date and features ultra-high-bypass ratio engines, and advanced aerodynamics and structures. Fundamentally, this aircraft follows similar design choices and methodologies as the current generation of commercial aircraft and simply represents an incremental evolution in the current state-of-the-art technology. All of the aircraft in the ERA portfolio, including the TW160, were designed with a balanced approach to simultaneously meet aggressive goals for reductions in fuel burn, emissions, and noise, and so represent feasible aircraft designs that balance cost, environmental, and community annoyance concerns.

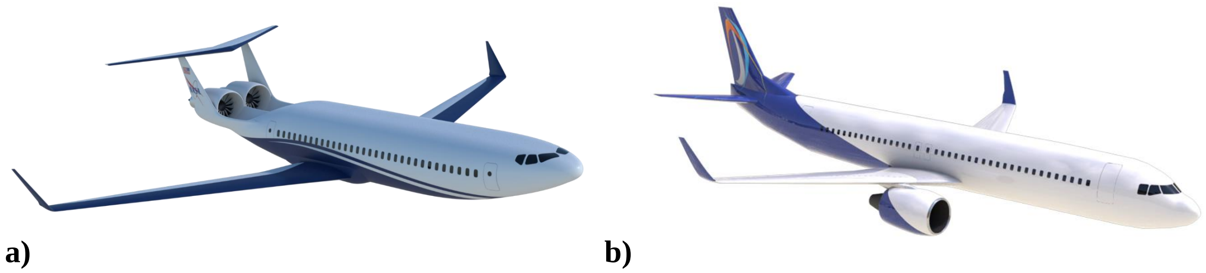

Fig. 1 Artist renderings of the a) ND8 and b) TW160 aircraft.

The present study is aimed at quantifying, on an equivalent basis, the expected noise performance of these two aircraft relative to each other and to the NASA Far Term noise goal, which is 42-52 EPNL dB cumulative below the Stage 4 FAA noise requirement. One of the most important differentiators between the two aircraft will be the unique Propulsion Airframe Aeroacoustic (PAA) effects relevant to each aircraft, described in more detail in Section III. The system noise of the two concepts will be predicted while including the most advanced and relevant noise reduction technologies expected to mature in the NASA Far Term time frame. It is important to note that certain technologies applicable to the TW160 may not be applicable to the ND8, and vice versa. Nevertheless, the predictions will feature a complete suite of noise reduction technologies suitable to each aircraft.

II. Noise Prediction Methodology

The NASA Aircraft NOise Prediction Program (ANOPP) provides the framework for the current noise prediction study. The models and methods contained in ANOPP are under continuous development, and the research-version code used in this study contains several models not present in the released version of ANOPP. The methodology adopted over the last several years during the ERA project places heavy emphasis on the use of relevant experimental data and physics-based methods, which are compatible with complex, unconventional aircraft. This is reflected in the addition of the GUO-LG [10], GUO-FLAP, and GUO-LE [11] modules. The current publicly-available version of ANOPP features mainly empirical or semiempirical relations, which are more suited to conventional aircraft design philosophies. The progression and development of the noise prediction process during the ERA project is discussed in detail in Thomas et al. [1]. An additional key advancement in recent years has been the ability to directly predict PAA effects, including engine noise shielding and reflection effects of the airframe, using experimental databases and unique data processing tools.

Figure 2 shows the overall noise prediction process and methods. The research version of ANOPP L31v6 is used within the ANOPP2 framework. A noise prediction begins with detailed information about the aircraft geometry, engine design and performance, and flight path. Several experimental datasets contribute to the design of the aircraft, as well as the noise source definitions. Integrated Technology Demonstration (ITD) efforts, summarized by Nickol and Haller [12], were undertaken during the last three years of the ERA project, and those results are also used to inform the models for advanced technologies associated with vehicles in the AATT portfolio. Each noise source is predicted individually and follows the flight path for each certification point, which is determined by the unique aircraft design. PAA effects are

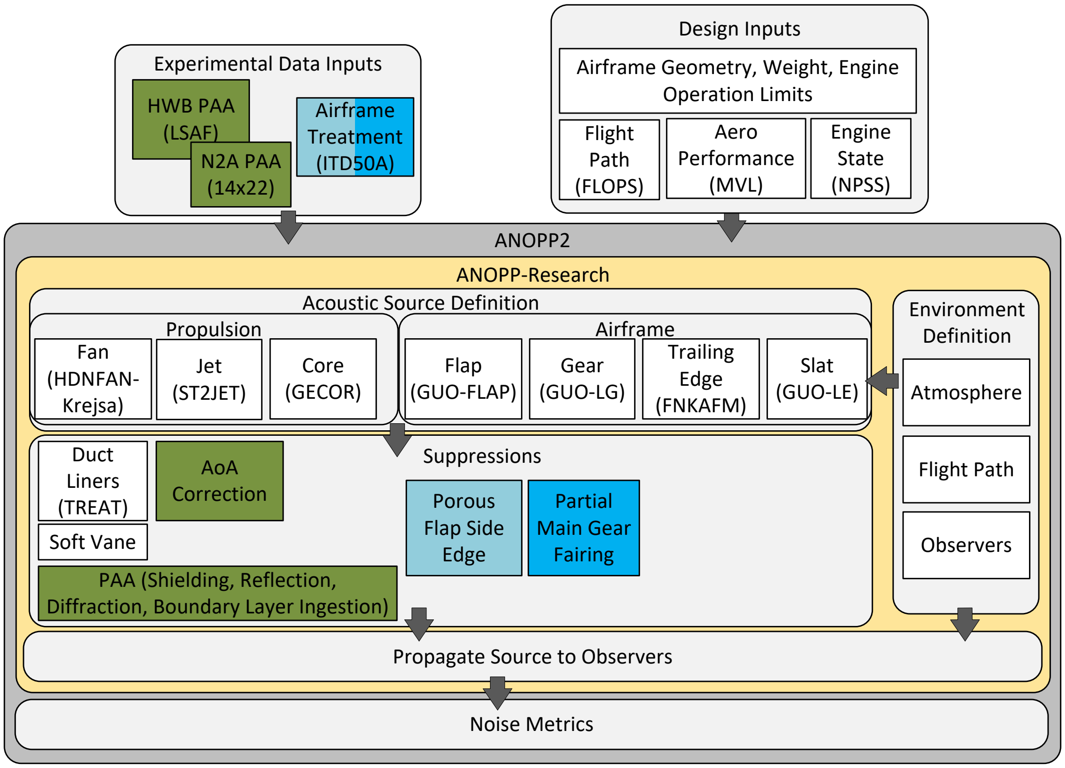

Fig. 2 Overview of the prediction process used in the current study.

evaluated for each engine source using experimental data before the noise is propagated through the atmosphere to ground observers. ANOPP provides one-third octave band spectra for each source and observer time as the aircraft flies overhead.

The final result of a noise prediction is the cumulative noise metric, described in overview in Figure 3. The noise metrics reported for all predictions are calculated as defined in 14 CFR Part 36 [3]. In order to obtain Federal Aviation Administration (FAA) certification to fly, the noise of an aircraft may not exceed certain noise levels defined using the Effective Perceived Noise Level (EPNL), as measured by following the guidelines in 14 CFR Part 36 [3]. Noise metrics must be met for the approach, lateral, and flyover locations, which correspond to the stages of flight with the greatest noise impact on communities surrounding airports. The maximum allowable EPNL at each certification point is defined by the aircraft weight and number of engines. These same metrics are used to evaluate future aircraft and noise reduction concepts in order to quantify their value on a system level using accepted standards. Noise predictions are performed at each certification point, resulting in individual EPNLs, which are then combined to arrive at the cumulative EPNL. The latest standard for certification is termed Stage 5. However, the NASA noise goals referenced in this and previous publications are written in reference to Stage 4 certification levels. For the advanced aircraft and noise reduction technologies evaluated in this study, the certification levels are reported as margins below Stage 4 to clearly define the benefit of these concepts in terms of NASA goals and in relation to previous studies.

III. Aircraft Definitions

As mentioned previously, the ND8 and TW160 were designed with NASA tools and assumptions for aerodynamics, structures, and propulsion, but with different entry-into-service dates. The NASA Numerical Propulsion Simulation System (NPSS) was first used to design the thermodynamic engine cycle for use on each aircraft. Next, the Weight Analysis of Gas Turbine Engines (WATE++) code was used to create an engine component architecture given the engine cycle generated by NPSS. Finally, the Flight Optimization System (FLOPS) was used to create full vehicle models with the proper sizing of airframe components. Overall size and performance parameters are given in Table 1.

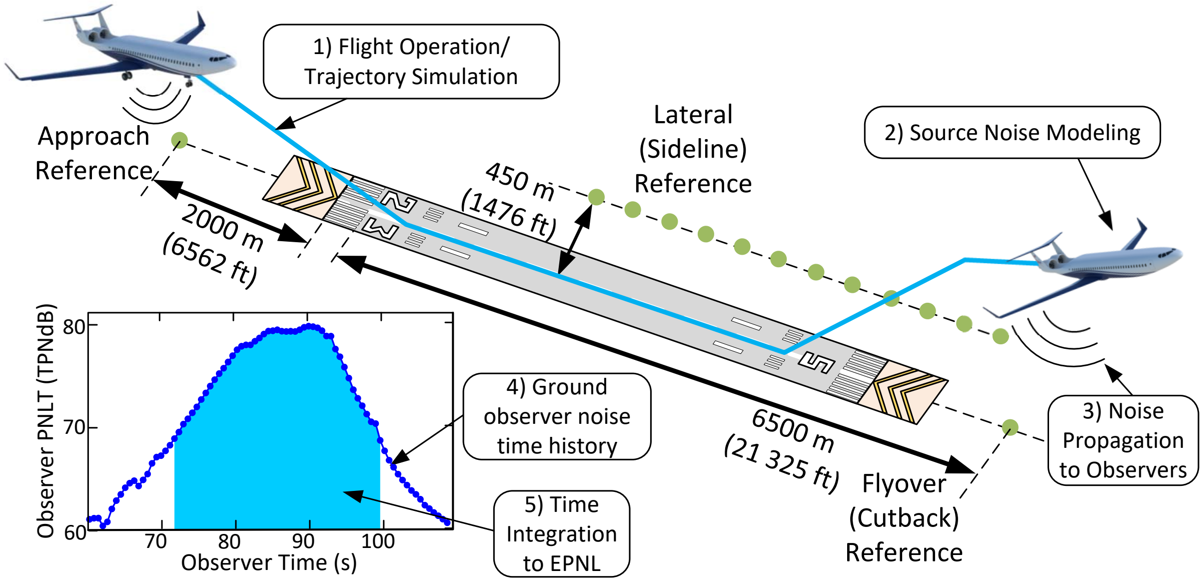

Fig. 3 Noise certification points with prediction methodology.

Table 1 Overall weight, size, and performance parameters for the ND8 and TW160.

	ND8	TW160
Takeoff Gross Weight (lb)	141,610	146,251
Balanced field length (ft)	8,000	7,386
Number of passengers	180	160
Range (nm)	3,000	2,875
Cruise Mach	0.78	0.78
Maximum Wing Chord (ft)	14.7	25.3
Minimum Wing Chord (ft)	5.1	4.2
Wingspan (ft)	118.2	113.9
Wing Leading Edge Sweep Angle (deg)	24	25
Fuselage Length (ft)	106.0	124.8
Fuselage Width (ft)	17.2	12.3
Fuselage Height (ft)	12.4	13.0

Several assumptions and aspects of the design process are relevant to noise and so will be highlighted here. The baseline engine architecture of both aircraft calls for dual two-spool geared turbofan engines. For the TW160, these engines are mounted below the wings in a conventional arrangement, but for the ND8, the engines are mounted within the pi-tail at the aft dorsal location on the fuselage. An important aspect of the engine design relates to the physical size constraints of the geared turbofan engines. Because the ND8 configuration dictates that the engines are placed within the pi-tail, the maximum fan diameter is limited to 1.82 m (72 inches). To meet maximum climb performance metrics, the fan pressure ratio (FPR) needs to be designed to provide enough thrust for a given fan diameter. The engine core is constrained to a minimum size, which reflects the expected physical limitations of core technology in the 2035 time frame [8]. The final design of the ND8 engine calls for a fan pressure ratio of 1.35 and a bypass ratio of 16 at takeoff conditions. This design is beyond the current state-of-the-art engines with maximum bypass ratios around 11 for this size class, but significantly less aggressive than the geared turbofan engines designed for the TW160 aircraft with a bypass ratio around 25 [1, 12, 13]. Other aspects of the ND8 and TW160 engines are given in Table 2. Key differences include the lower bypass ratio and higher fan blade tip speed of the ND8 engine, which lead to higher noise source levels.

Table 2 Engine parameters and takeoff (TO) conditions for the ND8 and TW160.

	ND8	TW160
Fan diameter (ft)	5.9	7.0
Number of fan blades	18	18
Number of fan stator vanes	40	40
Normalized rotor-stator spacing	1.52	1.52
Fan pressure ratio at TO	1.35	1.23
Bypass ratio at TO	16.0	25.5
Net thrust at TO (lb)	15,900	16,700
Fan RPM at TO	3670	2640
Fan blade tip Mach at TO	1.02	0.88
Aft duct liner L/H	1.95	1.83
Inlet duct liner L/R	0.96	0.68
Interstage liner effective L/H	0.34	0.27

The different placement of the engines also leads to different PAA effects for the two aircraft. Representative contour plots of the engine noise scattering by the airframe as a function of polar and azimuthal angle are shown in Figures 4 and 5 for a frequency of 1000 Hz. These contour maps were developed from unpublished experimental data collected in the Boeing Low Speed Aeroacoustic Facility (LSAF) during an experimental campaign described by Czech et al. [14]. Considering first the ND8, the engine placement above the fuselage at the aft location leads to significant shielding of the forward-radiated fan noise, but the presence of the pi-tail presents a reflecting surface for aft-radiated noise. For the ND8, it was assumed that jet noise would experience minimal reflections from the pi-tail, and those reflections would likely then be shielded by the fuselage, as the jet noise source location is well aft of the fan nozzle. As such, no scattering PAA effects were applied to jet noise during the ANOPP calculations. Scattering of core noise was assumed to be equivalent to that of fan noise due to their similar source locations. The effects shown here are consistent with those used in the initial system-level analysis of Clark et al. [9]. For the TW160, there are no shielding surfaces, as the engines have a direct line-of-sight to all observers. The engine-under-wing architecture leads to strong reflection of aft-radiated fan noise by the wing and high-lift system. The large reflecting surface also scatters jet noise in nearly all directions, as the source location is aft of the fan nozzle, under the wing.

The leading edge high-lift system on the ND8 consists of a conventional slat leading edge device, whereas the TW160 features a Krueger flap to enable natural laminar flow at cruise. Both aircraft feature a single element flap trailing edge device designed to approximate a continuous trailing edge that minimizes discontinuities between flap elements, a design element featured on some modern commercial airliners. This leads to a significant reduction in flap-side-edge noise compared to the reference aircraft (Boeing 737-800). Flight-condition-specific parameters for the high-lift system (flap deflection angles, etc.) are used for noise predictions at each stage of flight. The landing gear on both aircraft consist of a 737-type tricycle gear system with two wheels per main gear and nose gear.

In aircraft noise assessment, the flight profile plays a critical role since Mach number and angle of attack influence airframe noise source levels, and the flight path controls noise propagation distance to observers. Takeoff flight path information for the ND8, TW160, and a 737-like aircraft, are shown in Figure 6, and additional parameters are given in Table 3. The reduced thrust requirements at cruise due to boundary layer ingestion for the ND8 lead to reduced climb performance at takeoff compared to the reference aircraft. As a result, the ND8 is projected to reach an altitude 100 feet lower than a 737-like aircraft at the cutback certification point (21,325 feet downrange of brake release). This small difference is expected to have a minimal impact on certification noise, but is a departure from the TW160, which is expected to climb nearly 200 feet above the 737-like aircraft at the cutback point [13]. Aircraft speed at each of the three points also plays a role in total certification noise. The slower speed of the ND8 compared with other aircraft may lead to reduced source noise of airframe components, but is unlikely to have an effect on engine noise source levels. In fact, a slower flight speed is detrimental if the aircraft is engine-noise dominant, as slower speeds lead to longer integration

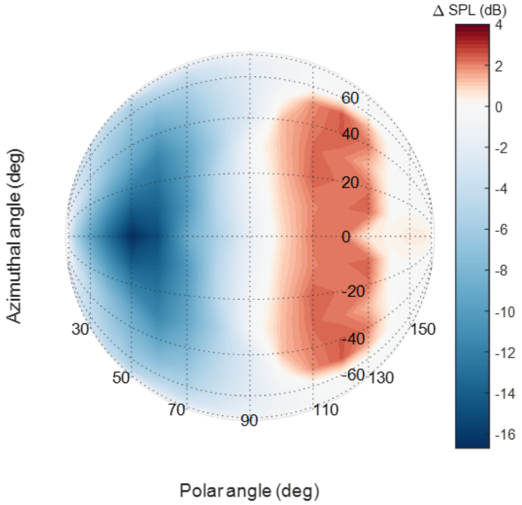

Fig. 4 Shielding and reflection of fan and core noise by the airframe of the ND8 for 1000 Hz as a function of polar and azimuthal angle. Direction of flight is from right to left, where 0 deg polar angle refers to the nose and 90 deg azimuth refers to the starboard wing.

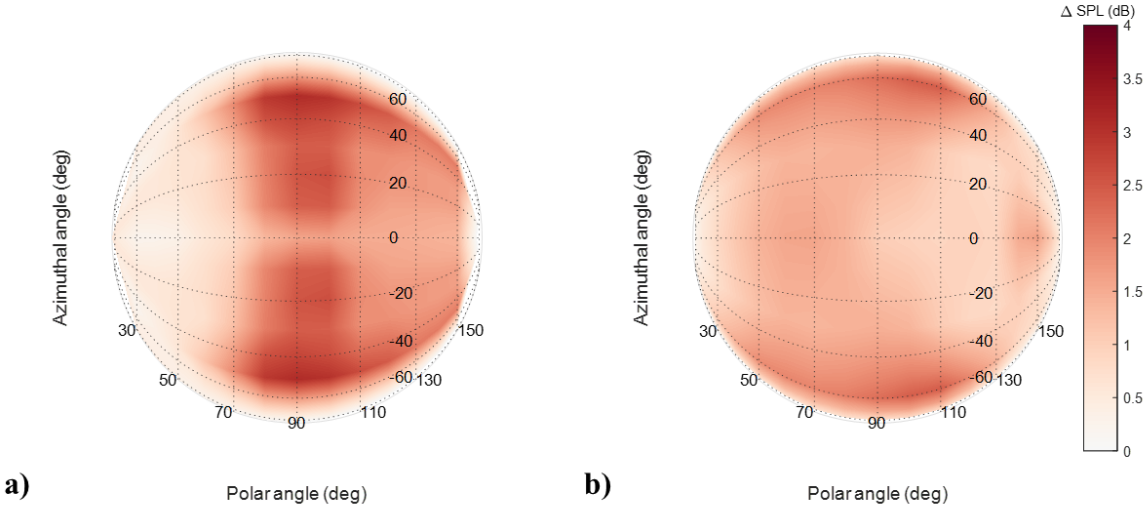

Fig. 5 Shielding and reflection of a) fan, core, and b) jet noise by the airframe of the TW160 for 1000 Hz as a function of polar and azimuthal angle. Direction of flight is from right to left, where 0 deg polar angle refers to the nose and 90 deg azimuth refers to the starboard wing.

times in the EPNL calculation.

System noise levels have been assessed previously for both the TW160 and ND8. The TW160 was last assessed in 2016 by Thomas et al. [13], wherein the cumulative margin to Stage 4 was predicted to be 30.1 EPNdB. However, with noise reduction technologies explored by the Integrated Technology Demonstrator (ITD) efforts of the ERA Project, the margin was predicted to increase to 31.4 EPNdB. These technologies included soft vane treatment, multiple-degree-of-freedom (MDOF) liners, partial main gear fairings, and flap side edge treatments. Each technology had been validated experimentally in a representative environment at the time of that study, which made them feasible

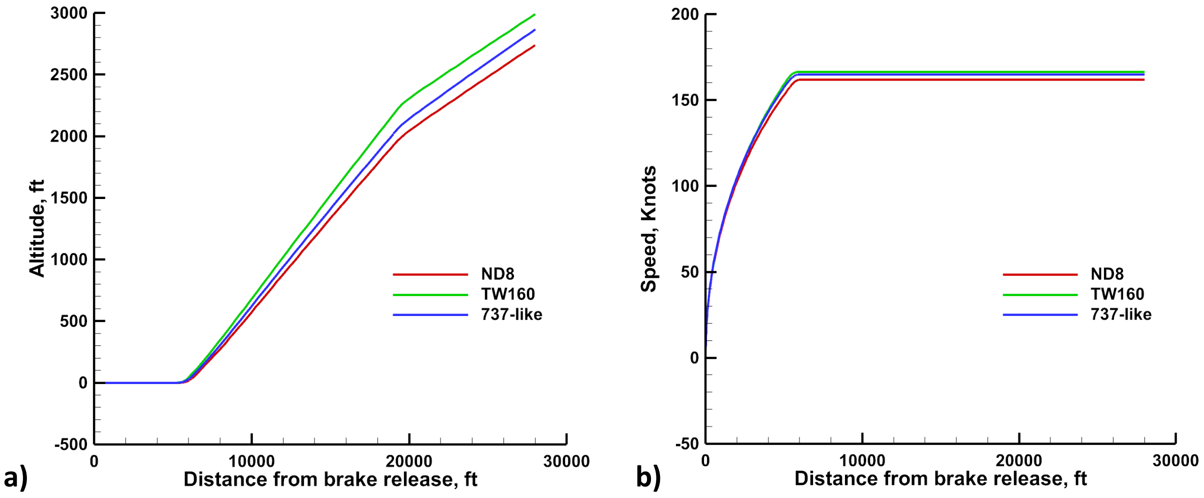

Fig. 6 a) Flight path and b) speed schedule of the ND8, TW160, and 737-like aircraft.

Table 3 ND8 flight path parameters compared to those of the TW160 and 737-like aircraft.

		Climb Angle (deg)	Angle of Attack (deg)	Thrust Fraction	Speed (knots)
Approach	ND8	-3.0	7.7	0.17	145
	TW160	-3.0	6.1	0.19	149
	737-like	-3.0	6.5	0.12	149
Sideline	ND8	8.6	6.8	1.00	162
	TW160	9.5	6.6	1.00	167
	737-like	9.0	6.9	1.00	165
Cutback	ND8	5.0	7.4	0.75	162
	TW160	4.9	7.3	0.68	167
	737-like	5.3	7.6	0.76	165

for use in the Mid Term time frame. The PAA effects of the TW160, primarily the reflection of fan and core noise from the underside of the wing, were computed to increase cumulative noise by approximately 5.5 EPNdB.

The ND8 was assessed recently in 2018 by Clark et al. [9] in order to establish a baseline noise level. The prediction included the same Mid Term level noise reduction technologies that were included on the assessment of the TW160. Significant effort was made to quantify the acoustic effect of boundary layer ingestion (BLI) on fan noise. Other PAA effects including shielding of the engine noise by the fuselage upstream and reflections of engine noise from the pi-tail were also quantified and incorporated into the prediction. With all PAA effects included, the ND8 was predicted to hold a cumulative margin to Stage 4 of only 7.4 EPNdB, due primarily to a 15 EPNdB system level noise penalty associated with BLI. If BLI noise were to be suppressed by a boundary layer diverter or other method of flow control, the ND8 would reach a noise margin of 22.4 EPNdB. A key noise factor was the limit placed on the engine diameter (and by extension the bypass ratio) by the placement of engines within the pi-tail. It was found that the dominance of aft-radiated fan noise (even without the BLI acoustic effect) limited the utility of the forward shielding provided by the fuselage. Additionally, noise reflections from the pi-tail only added to the fan noise radiated in the aft direction.

IV. Noise Reduction Technologies

As mentioned in Section III, prior noise assessments of the TW160 and ND8 included Mid Term level technologies, which are applied here before application of Far Term technologies. Multiple-degree-of-freedom acoustic liners are applied to all engines using the specified duct length and height from the NPSS engine definition. An interstage liner is included with an assumed effectiveness of 50%. The effects of soft vane liner technology along with sweep and lean of the stator vanes are included in the modeling of fan noise. The effect of porous flap side edge technology [15] is included in flap noise modeling. Finally, a partial main gear fairing [15, 16] is included in the modeling of main gear noise. All implementations of noise reduction technologies are consistent with prior studies [1, 2, 9, 13]. These technologies are included on the baseline aircraft of this study, and more advanced Far Term noise reduction technologies will be incrementally added to each aircraft. In cases where two technologies are incompatible and/or overlapping, for example, partial main gear fairing and pod gear, the effect of the earlier technology will be removed prior to adding the more advanced one.

It is noted here that two versions of the ND8 will be carried forward throughout this roadmap. The two versions are differentiated by whether or not the acoustic effects of BLI are included in the noise prediction. Because of the large 15 EPNdB cumulative penalty associated with BLI, a boundary layer diverter or active flow control system would be a desirable design feature to be used at community noise conditions (approach and departure). Such a system could then be deactivated at cruise in order to take advantage of the expected fuel savings associated with BLI. However, such a system is likely to be complex and heavy, such that further design work and trade studies must be undertaken to determine whether the advantages of such a system outweigh the costs. Therefore, we consider both scenarios through this roadmap to further inform this future decision in terms of the expected acoustic benefit.

Several Far Term technologies in the AATT portfolio are focused on reducing fan noise, which is a dominant noise source on both the TW160 and the ND8. A selection of technologies is shown in Figure 7. First, acoustic liners will be added to the engine bifurcation structure. In the previous work [9, 13], bifurcation liners were not added due to the relatively thin bifurcations found in small engines. However, discussions with Subject Matter Experts have led to the conclusion that the addition of liners would require thickening the bifurcation by only a few inches, which is acceptable within the framework of this study. The addition of bifurcation liners will impact the fan noise radiated in the aft direction, precisely the region that will have the maximum impact on system level EPNL. The effect of the bifurcation liner is modeled in ANOPP-Research through an effective increase in the quantity *L/H* of the aft duct, which determines the magnitude of noise attenuation achieved by the aft duct liner. The frequency range of attenuation is not modified by the bifurcation liner. This is equivalent to adding additional lined area to the aft duct, and no attempt is made to model the unique effects of placing the lined area on the bifurcation itself. To further reduce fan noise, an over-the-rotor acoustic liner (placed in the rub strip area around the fan) will be incorporated into the fan noise prediction. Over-the-rotor liners have had successful proof-of-concept demonstrations [17, 18], and are seen to have the potential for fan noise reduction across a wide range of directivity angles. Data from these preliminary experiments are used to determine a relative reduction in fan noise for use in ANOPP.

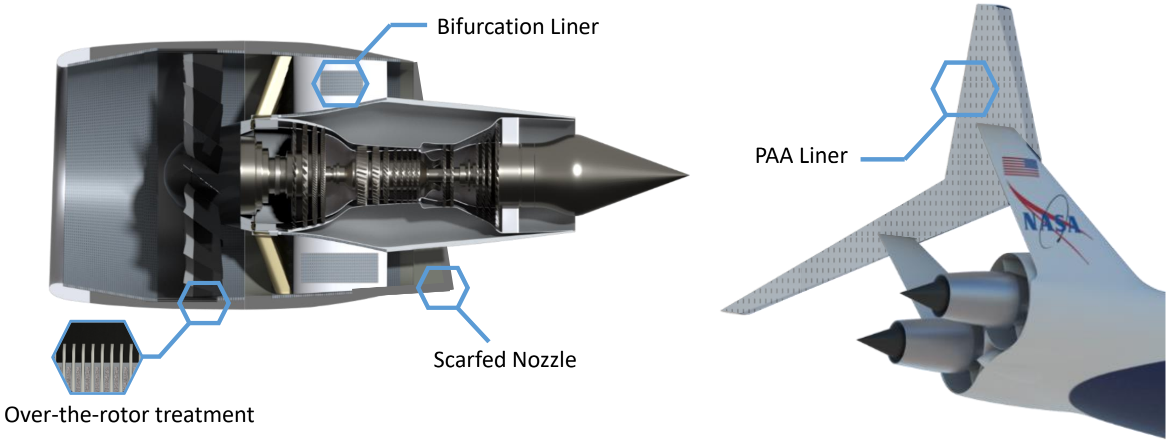

Fig. 7 Artist renderings of the noise reduction technologies applied to the ND8 engine and aft section.

Both the TW160 and ND8 feature unfavorable PAA effects related to reflections from the main wing and pi-tail, respectively. These will be addressed through the use of PAA liner technology, an acoustic liner embedded in the lower surface of either the main wing or horizontal stabilizer. A similar PAA liner has shown a successful proof-of-concept experiment with a counterrotating open rotor propulsion noise source with the effects of forward flight [19]. The development of lower drag facesheets for acoustic liners [20, 21] aids the practical implementation of this technology. The effect of PAA liners is modeled through a modification of the computed PAA effects discussed in Section III. The magnitude of reflections from the main wing or pi-tail are reduced by a factor of 2 (on a pressure-squared basis) in the angular regions corresponding to placement of PAA liners for maximum impact on community noise. The liners are expected to be effective over a frequency range of 1-2 kHz, which is both important for EPNL calculation as well as inclusive of prominent BPF harmonic tones.

On the ND8, a negative scarf is incorporated into the fan exit nozzle in order to increase the aft-shielding of fan noise. The negative scarf lengthens the bottom of the fan nozzle relative to the top, leading to reflection of fan noise away from ground observers. As this leads to a fan noise reduction in overhead and mild aft angles, this could have a significant impact on system level noise. The acoustic effect of the scarf nozzle is determined using unpublished experimental data from a wind tunnel test campaign jointly conducted by Boeing and NASA in Boeing's LSAF [22]. As part of that campaign, a broadband noise simulator was placed inside two different engine nacelle simulators, one with a scarf nozzle and one without. The effects of forward flight were included. Far-field acoustic data from that experiment form the basis of the model implemented in ANOPP.

On the TW160, because of the much larger reflecting surface formed by the main wing above the aft fan nozzle, the scarf nozzle was not seen as a viable technology since any redirected noise from the scarf would be reflected back toward the ground by the wing. Instead, a negatively scarfed inlet was considered for the tube-and-wing configuration. Scarfed inlets have been investigated previously [23, 24], with the findings indicating that this feature can achieve appreciable noise reduction by altering the directivity of the forward-radiated fan noise. The primary barrier to the introduction of this technology has been the aerodynamic challenges associated with a negatively scarfed inlet. In fact, a positively scarfed inlet, with the top of the inlet jutting forward relative to the bottom, is more beneficial to fan and nacelle performance, as this configuration helps to guide flow into the inlet, particularly at high angles of attack. A negatively scarfed inlet must be designed carefully in order to mitigate flow separation at the bottom of the inlet during high angle of attack conditions. However, prior studies conducted by industry experts [25] suggest that this challenge is not insurmountable, and an appreciable level of negative scarf can be incorporated into the inlet while still meeting all aerodynamic and performance requirements. To model the acoustic effect of this technology, a similar dataset as that used previously to model the scarf nozzle is used, although in this case, data including the effects of forward flight are not available.

To further reduce inlet-radiated fan noise, an inlet lip liner is applied to both vehicles by extending the effective length of the inlet liner to the full length of the inlet, where normally the inlet liner would be assumed to extend only from the fan casing to the throat. This technology has been tested previously [26] with promising results. The lip liner is seen as an important technology to develop as further increases in bypass ratio drive shorter inlets. Although challenges remain with regard to icing protection, aerodynamic drag, and inlet off-design performance, it is expected that development of this technology will continue to address these challenges in the Far Term time frame. It is expected that this technology will be much more effective on the TW160, as the inlet-radiated noise of the ND8 is largely shielded by the fuselage, but it is nonetheless included on both vehicles for completeness, as no aspect of the ND8 precludes its use.

With the addition of these technologies, fan noise may be reduced to a level where other noise sources may become important at the system level. To address core noise, a folding cavity liner can be applied to the center plug of the engine. The perforated face sheet covers the converging section of the core nozzle plug. This feature has been tested previously on a GE CF34 engine [27, 28]. Based on published results, an attenuation of just over 8 dB at 400 Hz, with a rapid roll off at higher and lower frequencies, is applied to core noise at all engine conditions and emission angles.

For both the TW160 and ND8, leading edge noise is seen as a significant source of noise, particularly on approach. Because the two aircraft feature two different types of leading edge high lift devices (slats on the ND8, Krueger flaps on the TW160), different technologies are applied to the two aircraft, but they share many similarities. Specifically, on the ND8, a slat cove filler is applied, whereas a Krueger dual use fairing is applied to the TW160. Development of a slat cove filler has been ongoing for several years [29], with one enabling technology being the recent advances in shape-memory alloy (SMA) slat cove fillers [30] that can be stowed and deployed automatically as the slats are retracted and extended. A Krueger dual use fairing is still in the concept development phase [2], but is based on the same principles as the slat cove filler and is therefore considered to have sound physical basis in existing technology. The Krueger dual use fairing is named as such due to its two primary acoustic benefits. The first is the aforementioned similarity to the slat cove filler, whereby the fairing acts to smooth the flow past the cove of the Krueger flap. The second use is related to the fairing's ability to partially cover the relatively large brackets that are required to actuate the Krueger flap mechanism. These brackets are much larger than those found on traditional slats, and are therefore a more prominent noise source. For the acoustic modeling of the slat cove filler, a prediction method [31] that directly handles the noise from a cove filler is utilized to compute the noise reduction. The Krueger dual use fairing is assumed to transform the Krueger device into a streamlined shape, very similar to a slat with a cove filler installed. It is therefore assumed that the noise from a Krueger with a dual use fairing will be approximately the same as an equivalent slat with a cove filler, as the physical features of these two structures are similar. The process of indirectly quantifying the dual use fairing effectiveness in this way is due to the lack of relevant experimental data, which will need to be addressed to mature this technology.

In addition to the fairings on the leading edge devices, a further effect is considered in which the gap between the trailing edge of the slat/Krueger and the leading edge of the main wing is sealed. This could be accomplished using a structure similar to a slat gap filler [32] and would eliminate the high speed flow between the two wing elements that is a significant source of noise for both the slat and Krueger. Of course, sealing this gap runs counter to the high-lift performance benefit of including a slat/Krueger. However, with continual improvements being made to the aerodynamics of high-lift systems, it is anticipated that this will be a viable configuration in the Far Term time frame. It is noted here that this technology is only required at approach conditions; as for the vehicles considered here, no gap is assumed to be present during takeoff conditions. The GUO-LE module within ANOPP-Research has the ability to handle a sealed gap configuration, directly computing the noise in this case.

A concept of relevance to trailing edge flap noise is the continuous moldline link (CML) flap. The concept arises from the understanding that one of the primary sources of flap noise is the rollup vortex in the cross flow at the side edge. By effectively blending the flap side edge into the main wing element, the CML flap reduces or eliminates this vortex, achieving significant noise reduction. An acoustic model for this effect is developed by considering both the low- and high-frequency flap side edge noise sources, which scale on flap chord and thickness, respectively. Using data from a small scale wind tunnel test [33], a maximum expected noise reduction for each component is established. A functional roll-off of noise reduction with respect to frequency and directivity angle is then assumed to fill out the model. It is worth noting that the effectiveness of the CML flap within this roadmap study may be tempered by the fact that the baseline aircraft already assume two low noise concepts as described in Section III, namely the continuous trailing edge flap system that minimizes discontinuities between adjacent flap elements, as well as the porous flap side edge treatment that is considered a Mid Term level technology.

The final prominent noise source to be discussed is the landing gear of the two aircraft. Here, vehicle configuration plays a large role in determining the options available for noise reduction. With the conventional engine placement of the TW160, the only viable option for noise reduction is to place a fairing on the nose gear. Although the nose gear is not typically a significant noise contributor, it may play a larger role as other noise sources are attenuated. Of course, this technology can also be applied to the ND8. However, with the ND8's engines above the fuselage, the pod gear concept [4] presents a feasible alternative to the conventional main gear arrangement. With the gear placed in non-load-bearing pods, which act as large fairings around the complex struts, supports, and hydraulic systems present on the main gear, flow around the gear is smoothed considerably, leading to reduction of noise at the source. In addition, noise absorbing liners placed within the pod cavity help to attenuate any reflected noise from the exposed gear components. Finally, an axle fairing placed around the main gear axle further contains radiated noise within the pod structure. The acoustic impact of this technology is computed using a physics-based method that accounts for the propagation of noise from the main gear structure around the pod and axle fairing.

V. Results and Discussion

Table 4 shows a summary of the technologies to be applied to each aircraft. For this roadmap study, the noise reduction technologies are evaluated in two ways. The first involves a sequential buildup of technologies, wherein the most effective technology is applied first, followed by the next most effective, and so on. The second method is utilized upon completion of the sequential buildup; once all technologies have been applied, yielding the final Far Term configuration, each technology is removed individually, one at a time, in order to evaluate the effectiveness of that technology on the final configuration. This "one-off" process removes the sequential bias inherent in the first method, and evaluates all technologies on an equal basis.

Table 4 Complete list of all Far Term noise reduction technologies applied to the ND8 and TW160.

Technology	Noise Component	ND8	TW160
Scarf Nozzle	Aft Fan	X	
Scarf Inlet	Forward Fan		X
Lip Liner	Forward Fan	X	X
Over-the-Rotor	Fan	X	X
Bifurcation Liner	Aft Fan	X	X
PAA Liner	Aft Fan Reflection	X	X
Center Plug Liner	Core	X	X
Slat Cove Filler	Leading Edge	X	
Krueger Dual Use Fairing	Leading Edge		X
Sealed Slat/Krueger Gap	Leading Edge	X	X
CML Flap	Flap Side Edge	X	X
Pod Gear	Main Gear	X	
Nose Gear Fairing	Nose Gear	X	X

A. ND8 System Noise

As mentioned previously, two versions of the ND8 will be carried forward through the roadmap, one including all PAA effects, and one that assumes the acoustic effect of BLI on fan noise is suppressed. Before considering the effects of adding individual technologies, it is useful to examine the ranking of noise sources for each configuration prior to adding Far Term technologies. Figures 8 through 10 show PNLT curves at each of the three certification points. It is clear that including all PAA effects leads fan noise to dominate the peak PNLT at all three certification points and to be the dominant source at takeoff conditions even to the 10 dB down point relevant to EPNL calculations. This makes it clear that noise reduction technologies applied to other sources will have a minimal impact on the system-level cumulative noise. The possible exception is slat noise on approach, where the engine throttle (and therefore noise) is minimized and slat noise comes within 10 dB of the fan noise.

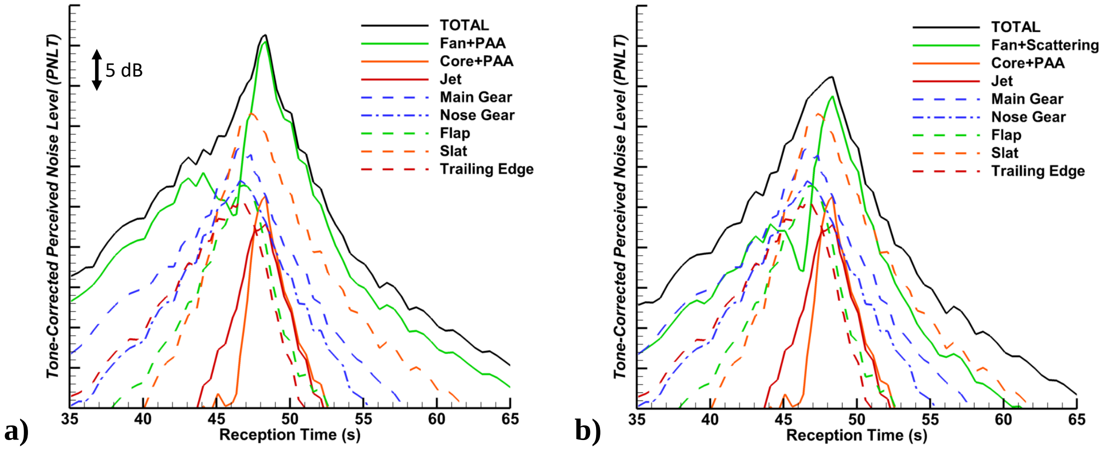

Fig. 8 PNLT curves of the noise received by the approach observer for the ND8 a) with all PAA effects and b) with BLI suppressed.

With the effect of BLI suppressed, fan noise is less dominant at all points, and this presents more opportunities for noise reduction using technologies that target a more diverse set of sources. On approach, slat noise is a dominant source that is within 3 dB of fan noise. Main gear noise is also a significant component of noise, particularly at forward

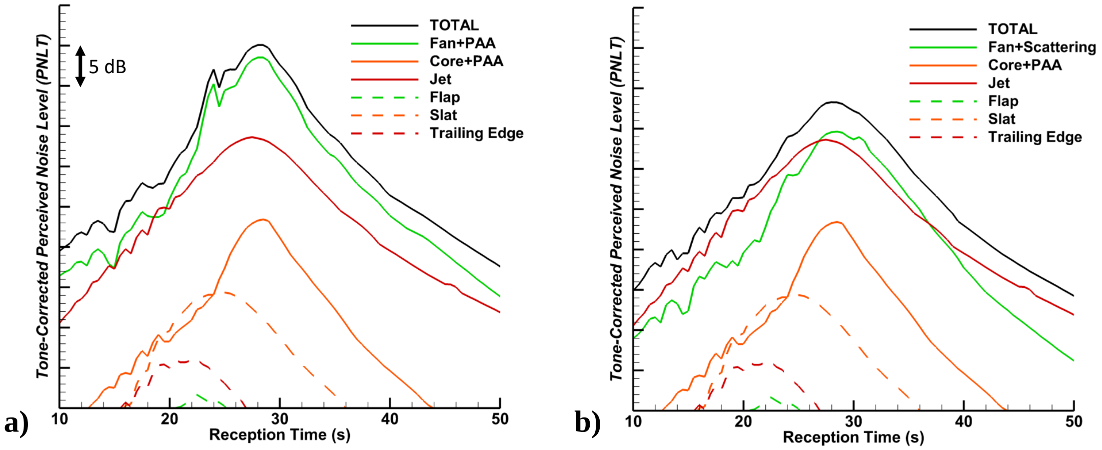

Fig. 9 PNLT curves of the noise received by the lateral observer for the ND8 a) with all PAA effects and b) with BLI suppressed.

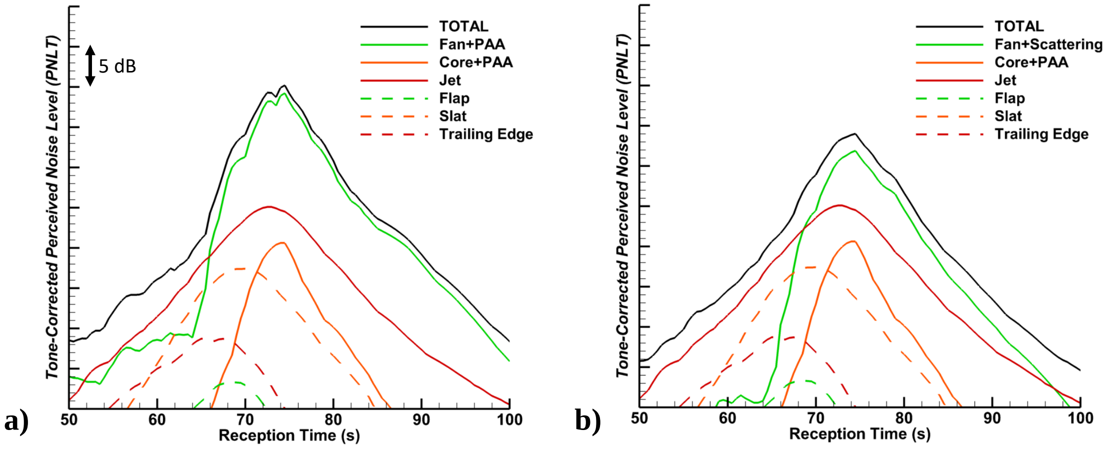

Fig. 10 PNLT curves of the noise received by the flyover observer for the ND8 a) with all PAA effects and b) with BLI suppressed.

emission angles (as the aircraft approaches the observer). On takeoff, the fan and jet noise contribute nearly equally to the total noise levels measured by the lateral observer. Finally, fan noise still remains dominant at the flyover observer, as this location is most influenced by aft fan noise reflections from the pi-tail.

With these source rankings in mind, we now consider the system-level noise impacts of the technologies described above. Table 5 shows the results of the sequential buildup and one-off analysis for the ND8. It is clear that the scarf nozzle has the greatest impact on the system noise of the ND8, whether or not BLI is included in the acoustic modeling. This is because the scarf nozzle targets aft fan noise specifically, which is, by far, the dominant source for the ND8 as described above. The over-the-rotor liner also targets fan noise in general, which makes it the second most effective technology for both configurations. It is here that the two configurations begin to diverge in terms of order of effectiveness for subsequent technologies. With all PAA effects, fan noise is more dominant, and as such, the bifurcation liner has the greatest impact of the remaining technologies. The cove filler follows, along with the PAA liner and pod gear concepts. With BLI suppressed, the cove filler and pod gear are more effective than the bifurcation liner and PAA liner due to the altered source ranking. In fact, the cove filler is nearly twice as effective on an EPNL level on the

ND8 with BLI suppressed as it is with all PAA effects included. The center plug liner, sealed slat gap, and nose gear fairing have milder effects, together adding up to 0.5 EPNdB reduction with all PAA effects and 0.9 EPNdB with BLI suppressed. For this aircraft, the CML flap and lip liner have a negligible impact on the noise.

Table 5 System-level impacts of noise reduction technologies on the ND8. Values given are ∆EPNL.

All PAA Effects				BLI Suppressed		
Technology	Buildup	One-Off	Rank Change	Technology	Buildup	One-Off
Scarf Nozzle	-3.3	-3.3	—	Scarf Nozzle	-2.1	-2.2
Over-the-rotor liner	-1.5	-1.7	—	Over-the-rotor liner	-1.0	-1.1
Bifurcation Liner	-0.8	-0.8	↑1	Cove Filler	-1.0	-1.3
Cove Filler	-0.6	-0.7	↑2	Pod Gear	-0.5	-0.7
PAA Liner	-0.6	-0.7	↓2	Bifurcation Liner	-0.5	-0.5
Pod Gear	-0.4	-0.3	↓1	PAA Liner	-0.4	-0.4
Center Plug Liner	-0.2	-0.2	↑1	Sealed Gap	-0.3	-0.3
Sealed Gap	-0.2	-0.2	↓1	Center Plug Liner	-0.3	-0.3
Nose Gear Fairing	-0.1	-0.1	—	Nose Gear Fairing	-0.3	-0.3
CML Flap	0.0	0.0	—	CML FLap	-0.1	-0.1
Lip Liner	0.0	0.0	—	Lip Liner	0.0	0.0
Total	-7.7			Total	-6.5	

The effectiveness, or lack thereof, of the CML flap and lip liner, in addition to the predicted effect of the pod gear, warrant some further explanation to put these results in context with the present study. It is important to remember that both the pod gear and CML flap, which are Far Term technologies, replace the partial main gear fairing and porous flap side edge, which are Mid Term technologies. Furthermore, the flap system is already acoustically modeled assuming the continuous trailing edge architecture that minimizes the discontinuities between flap elements and the main wing. As such, the component-level noise reduction that occurs when transitioning from porous flap side edge to CML flap is much smaller than, for example, if the CML flap were to be applied to an untreated flap with a more traditional design architecture with large discontinuities between elements. This, together with the fact that flap noise is not a dominant source on the ND8, explains the ineffectiveness of this technology, but this is only applicable to this configuration. As main gear noise is a somewhat more dominant source than flap noise, the pod gear registers with a larger effect than CML at the system level. It is still fair to say, however, that the pod gear as applied here to a two-wheel main gear is less effective than the pod gear applied previously [1, 2] to the six-wheel gear featured on larger aircraft, both due to the higher source ranking of gear noise on those larger aircraft, in addition to the higher component-level noise reduction that the pod gear achieves for a six-wheel gear by shielding a much more complex and noisy structure. In a similar way, the lack of any system-level noise reduction by the lip liner is explained simply by the fact that inlet noise is almost entirely shielded by the ND8 fuselage, and is therefore not a noise source that contributes to the overall EPNL. The lip liner can be a useful technology for other configurations, as will be seen during the discussion of the TW160 results.

The results of the one-off analysis are largely consistent with the results of the sequential buildup, signifying that the source ranking of the Mid and Far Term configurations of the ND8 are similar. With all PAA effects included, the complete portfolio of Far Term technologies achieves a 7.7 EPNdB reduction in the cumulative system noise of the ND8. Likewise, with the acoustic effect of BLI suppressed, the same portfolio reduces the system noise of the ND8 by 6.5 EPNdB. Considering now the total system noise of the ND8, and how this relates to the NASA Far Term goals, Table 6 shows the final cumulative noise level for the ND8. The Mid Term aircraft designates the same configuration that was evaluated previously by Clark et al. [9]. However, as updates are continuously made to ANOPP, and as the detailed definition of the aircraft continues to evolve, the overall noise levels are correspondingly updated to reflect these changes, leading to the slight differences seen here with respect to the previous study. The Far Term aircraft designates the final configuration with all Far Term noise reduction technologies applied. With all PAA effects, the portfolio of technologies nearly doubles the ND8 margin to Stage 4, representing a significant improvement overall. With BLI suppressed, the ND8 approaches 30 EPNdB below Stage 4. However, as evidenced by the comparison with NASA goals, this aircraft

Table 6 Cumulative noise margins to certification of the ND8.

	Margin to Stage 4 (Stage 5), EPNdB	
Configuration	Mid Term Aircraft	Far Term Aircraft
NASA Goal	32 - 42	42 - 52
ND8 w/ All PAA Effects	8.7 (1.7)	16.3 (9.3)
ND8 w/ Scattering Only	22.8 (15.8)	29.2 (22.2)
System-Level BLI Penalty	14.1	12.9

falls well short of the needed noise performance of future aircraft concepts, particularly the (more realistic) case of the ND8 with all PAA effects included. The acoustic BLI penalty is also presented in Table 6 for both Mid Term and Far Term configurations. It is worth noting here that the acoustic BLI model used in this study has not changed from that described in Clark et al. [9], but rather the change in source ranking between the Mid and Far Term aircraft leads to a difference in the system-level impact of the increased fan noise due to BLI. The reduction in fan noise due to the Far Term technologies results in a lessening of the impact of BLI, from 14.1 to 12.9 EPNdB.

B. TW160 System Noise

Following the same analysis procedure as for the ND8, we first begin our discussion by considering the PNLT profiles of the TW160 at each certification point as shown in Figure 11. As with the ND8, there is a strong dominance of fan noise at all three certification points, due primarily to the wide angular range over which reflections from the wing increase fan noise. The reflections are strongest in the aft direction, and this is most noticeable from the approach observer location where there is a sharp increase in noise as the aircraft flies overhead. The next strongest sources at approach are the Krueger flap, main gear, and trailing edge flaps, although even the peak of Krueger flap noise is approximately 8 dB below the peak of fan noise. Likewise, at the lateral location, the peak jet noise is about 8 dB below the peak fan noise, and at the flyover location, core noise is well below fan noise, although the Krueger flap dominates at earlier times at this location.

With the source ranking established for the TW160, we can consider the effectiveness of the noise reduction technologies on the TW160 as shown in Table 7. At the top of the list as the most effective technology, the over-the-rotor liner again leads to about a 1.5 EPNdB decrease in the system noise, similar to the ND8. The scarf inlet is close behind, yielding about 1.3 EPNdB of noise reduction. The scarf inlet is notably less effective than the scarf nozzle on the ND8 because the aft-radiated fan noise is dominant, due to the natural source directivity of the GTF-like engines and the reflections from the wing. Next, the Krueger dual use fairing yields about 1.0 EPNdB of noise reduction. Although the Krueger flap is not the most dominant source, it is still significant at both the approach and flyover locations. In addition, the Krueger dual use fairing is effective at reducing two major subcomponents of Krueger flap noise, and thus yields a

Table 7 System-level impacts of noise reduction technologies on the TW160. Values given are ΔEPNL.

Technology	Buildup	One-Off
Over-the-rotor liner	-1.5	-1.6
Scarf Inlet	-1.3	-1.2
Krueger Dual Use Fairing	-1.0	-1.2
Bifurcation Liner	-0.8	-0.9
Center Plug Liner	-0.8	-0.9
Inlet Lip Liner	-0.5	-0.5
PAA Liner on Wing	-0.3	-0.3
CML Flap	-0.1	-0.1
Nose Gear Fairing	-0.1	-0.1
Sealed Krueger Gap	0.0	0.0
Total	-6.4	

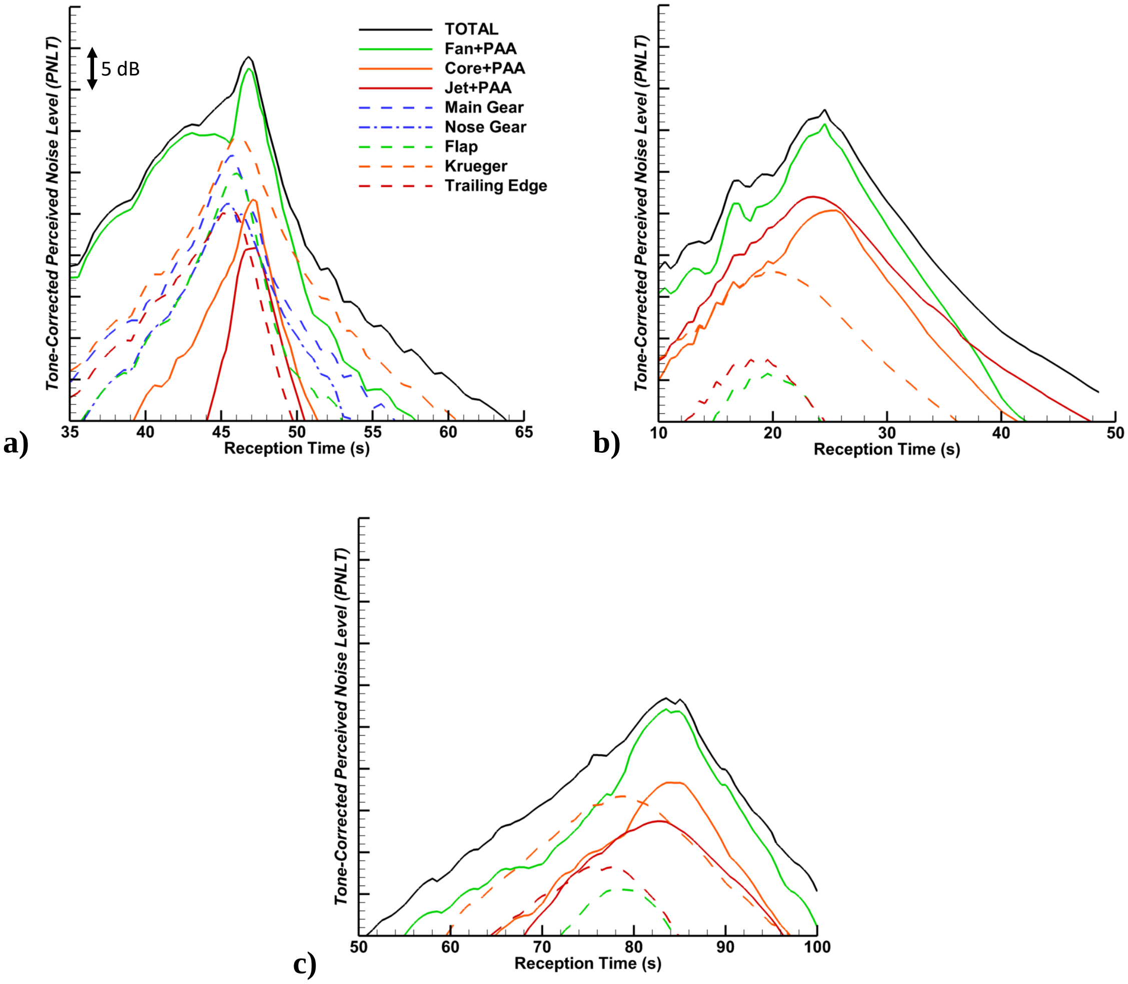

Fig. 11 PNLT curves of the TW160 noise received by the a) approach, b) lateral, and c) flyover observers.

strong reduction at the component level that translates to good performance at the system level for this aircraft. The bifurcation liner effectively reduces fan noise, and the center plug liner achieves a respectable system level reduction by addressing core noise, a significant component at the lateral and flyover observers. The lip liner achieves a 0.5 EPNdB reduction, contrasting the negligible effect on the ND8, as inlet radiated fan noise is a much more significant component on the TW160. The PAA liner on the wing reduces some of the reflections, and is good for another 0.3 EPNdB. The CML flap, nose gear fairing, and sealed Krueger gap on approach have minor effects at best. The discussion above on the CML flap as applied to the ND8 is again relevant here.

The results of the one-off study are again largely consistent with the buildup analysis. One interesting feature of the one-off analysis is that the Krueger dual use fairing has approximately the same impact on the final configuration as the scarf inlet, indicating that the Krueger noise is a more dominant component on the final Far Term configuration after the addition of all technologies that target fan noise. In total, the full portfolio of technologies achieves 6.4 EPNdB of cumulative noise reduction on the TW160. Table 8 shows the final system level cumulative noise metrics for the Mid Term and Far Term TW160. The recalculated Mid Term aircraft, incorporating all ANOPP and process updates, reaches 28.1 EPNdB below Stage 4, compared to 31.4 EPNdB as published in 2016 [13]. The PAA effects, including reflection of fan, core, and jet noise, were computed to increase the cumulative noise by 4.8 EPNdB. The final Far Term aircraft reaches 34.4 EPNdB below Stage 4. Although the Far Term technology portfolio yields a significant improvement in performance, the aircraft nevertheless falls short of the minimum Far Term goal of 42 EPNdB. In fact,

Table 8 Cumulative noise margins to certification of the TW160.

	Margin to Stage 4 (Stage 5), EPNdB	
Configuration	Mid Term Aircraft	Far Term Aircraft
NASA Goal	32 - 42	42 - 52
TW160	28.1 (21.1)	34.4 (27.4)

the Far Term aircraft margin is on the lower end of the Mid Term goal, indicating that this aircraft does not have the acoustic performance needed for future advanced aircraft concepts. Although the ultra high bypass ratio engines reduce engine noise overall, the unfavorable PAA effects of the TW160, with the large reflecting surface provided by the wing, counter this benefit at all certification observers.

VI. Conclusions

This paper has presented the first Far Term noise reduction roadmap for single-aisle class vehicles in the 160- to 180-passenger range. Two advanced aircraft concepts, one conventional and one unconventional, were evaluated using NASA's latest prediction methods contained in ANOPP-Research, with technology portfolios tailored to each concept based on compatibility with their configuration and layout. The realistic component-level performance of each technology was developed based on experimental and numerical data. The technologies were evaluated with respect to their total expected impact at the system level, utilizing standard certification procedures as a uniform method of assessment.

In total, eleven technologies were included in the ND8 portfolio, while ten technologies comprised the TW160 portfolio. For the ND8, system-level cumulative noise was reduced by 7.7 EPNdB relative to the Mid Term aircraft when all PAA effects were included in the simulation, whereas the benefit was 6.5 EPNdB for the same set of technologies when the acoustic effect of BLI was suppressed. Similarly, the total benefit was predicted to be 6.4 EPNdB for the TW160 aircraft. The technologies of most benefit were those that targeted fan noise, either at the source or by modifying the propagation and scattering. The scarf exhaust nozzle was the most effective for the ND8, as it reflected fan noise away from ground observers in the aft direction where fan noise was most dominant. The over-the-rotor liner was the next most effective on the ND8, and proved to be the most beneficial technology on the TW160 followed by the scarf inlet. Technologies targeting airframe noise followed; the slat cove filler was more effective on the ND8 when BLI was suppressed than when all PAA effects were included, and the Krueger dual use fairing achieved a significant noise reduction for the TW160. Both of these technologies targeted leading edge noise, the dominant airframe noise source for these smaller vehicles. PAA liners on the tail and wing of the ND8 and TW160, respectively, yielded significant improvements by moderating the unfavorable PAA characteristics of the two aircraft. Certain technologies, such as the CML flap and pod gear, that achieve good component level noise reduction did not exhibit outstanding system level benefits, both due to the lower source ranking of the targeted components and because they replaced other Mid Term technologies that already targeted the same sources.

The goal of this study was to evaluate the prospects for these two aircraft concepts to reach NASA's Far Term noise goal. The unfavorable PAA effects of these two aircraft, with their lack of shielding and significant reflection of aft noise, plus the ND8's acoustic BLI penalty, lead to high noise levels for the baseline configurations of these two aircraft and make it very challenging to meet the Far Term goal after application of the technologies in this study. All of the technologies provide only a 6-8 EPNdB cumulative benefit, compared to a 10 EPNdB difference between the Mid Term and Far Term goals. This means that an aircraft must meet the Mid Term goal before application of Far Term technologies to have any chance of meeting the Far Term goal once those technologies are applied. This study reinforces the conclusion of prior studies on larger aircraft that the best method to reduce overall noise is through a configuration change to gain favorable PAA effects.

Of course, the aircraft configuration should not be the sole focus of noise reduction. Further development, maturation, and expansion of the Far Term technology portfolio is needed to improve the expected noise benefit, in particular for aircraft in this passenger class. The source ranking of these aircraft has shown that technologies to target the source and propagation of fan noise, especially that which is radiated in the aft direction, such as the scarf nozzle and PAA liner, have the greatest impact at the system level and could provide the most benefit with maturation. However, airframe technologies such as the Krueger dual use fairing and slat cove filler can also lead to appreciable reductions in system noise, and further development of these technologies is crucial not only to confirm the expected noise benefits, but also to bring about further advancements that can improve their performance. Finally, it must be emphasized that new and innovative concepts must be devised and added to the Far Term technology portfolio in order to improve the possibility of meeting the Far Term goals with any aircraft.

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