Far Term Noise Reduction Technology Roadmap for a Large Twin-Aisle Tube-and-Wing Subsonic Transport

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Interest in unconventional aircraft architectures has steadily increased over the past several decades. However, each of these concepts has several technical challenges to overcome before maturing to the point of commercial acceptance. In the interim, it is important to identify any technologies that will enhance the noise reduction of conventional tube-and-wing aircraft. A technology roadmap with an assumed acoustic technology level of a 2035 entry into service is established for a large twin-aisle, tube-and-wing architecture to identify which technologies provide the most noise reduction. The noise reduction potential of the architecture relative to NASA noise goals is also assessed. The current roadmap estimates only a 30 EPNdB cumulative margin to Stage 4 for this configuration of a tube-and-wing aircraft with engines under the wing. This falls short of reaching even the 2025 Mid Term NASA goal (32 EPNdB) in the Far Term time frame. Specifically, the lack of additional technologies to reduce the aft fan noise and the corresponding installation effects is the key limitation of the noise reduction potential of the aircraft. Under the same acoustic technology assumptions, unconventional architectures are shown to offer an 8–10 EPNdB benefit from favorable relative placement of the engine when integrated to the airframe.

Nomenclature

f = frequency
p = root mean square pressure
H = bypass aft duct height
L = sound pressure level, re 20 µPa
R = fan radius
$\mathcal{S}$ = suppression factor
θ = polar angle
ϕ = azimuthal angle

Subscripts
i = installed noise source
f = free field noise source

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I. Introduction

NASA has continuously applied effort to develop and mature unconventional aircraft architectures and technologies over the past several decades. More concentrated effort has been applied in the past two decades, most recently through work done in the Environmentally Responsible Aviation (ERA) Project, and currently through the Advanced Air Transport Technology Project. Both projects have been focused on reaching emission goals for future generations of aircraft as described in the NASA Strategic Implementation Plan [1]. Progressive emission reduction goals in noise, NO_x, and fuel consumption are set over three decades, with the Near Term beginning in 2015, Mid Term in 2025, and the Far Term in 2035. During ERA, focus on reaching all three emission goals simultaneously led to the development of several balanced aircraft configurations. Along with the unconventional architectures, the conventional architecture of a cylindrical fuselage with engines mounted under the wing was also assessed, providing a useful baseline. At the end of ERA, the performance of each of the architectures was quantified across several size classes with 2020 technology assumptions [2].

Since ERA, several noise reduction technology roadmaps have been designed to modify Mid Term configurations to the Far Term. This is done by adding relevant technologies to a particular concept architecture that are expected to mature to a technology readiness level sufficient for commercialization by 2035. Two technology roadmaps have already been completed for unconventional large twin-aisle architectures, the mid-fuselage nacelle [3] and hybrid wing body [4]. For the single-aisle class, a companion paper [5] details the roadmaps for the NASA version of the D8 and a conventional tube-and-wing aircraft. The study here provides an analysis of the noise reduction potential of the conventional tube fuselage with under-wing mounted engines for the large twin-aisle class. A secondary purpose of this work is to provide context to the previously completed roadmaps for the hybrid wing body and mid-fuselage nacelle architectures. Completion of these three roadmaps for aircraft in the same size class now allows for a quantitative comparison on the Far Term outlook of the noise reduction potential of unconventional aircraft relative to a conventional configuration in the Far Term time frame that was not available prior to this work.

The roadmap also allows for comparisons of the noise reduction potential of particular technologies across different architectures. Within this paper, an architecture is defined as the general layout and type of the individual subsystems of the aircraft (e.g., the fuselage type, or integration of the engine and airframe), while a configuration is a variation of included technologies on those subsystems or sizing of a particular architecture. Based on the acoustic source ranking, technologies can have varying impact on the overall noise reduction of two different aircraft configurations. One of the most influential effects on the source ranking of an aircraft relates to the integration of the propulsor and airframe. Based on the relative arrangement of the two subsystems, a variety of interactions can result, aptly known as propulsion airframe aeroacoustic (PAA) effects. There are two broad categories within the umbrella of PAA effects, source modification of noise generation due to aeroacoustic interaction between two aircraft elements (e.g., jet-flap interaction noise), and noise scattering effects due to the presence of surfaces in the acoustic propagation path. The certification noise impact of PAA effects between a hybrid wing body with dorsal mounted engines and a conventional tube-and-wing with under-wing mounted engines was previously assessed as 11.9 EPNdB [6]. Since that time, additional PAA effects have been modeled for the tube-and-wing aircraft.

This paper presents the process of modifying the 2025 Mid Term baseline tube-and-wing configuration into a 2035 Far Term configuration through a technology roadmap. This technology roadmap considers technologies likely to be developed within the period considered, using only those technologies that are expected to be beneficial to reducing the noise of the aircraft without significantly impacting the aircraft weight or design. First, the baseline Mid Term aircraft configuration is presented. Discussion then follows of the procedure used to model the noise. Following that, details of further modeling and parameter updates since the last published results are given. Results of the Mid Term aircraft will be briefly analyzed to develop a strategy for generating a Far Term technology roadmap. A description of all of the technologies used in the Far Term roadmap is provided next. Finally, the results of the Far Term roadmap are discussed and summarized.

II. Baseline Aircraft Configuration

The aircraft architecture considered here is the conventional cylindrical fuselage with podded engines integrated under the wing, as shown in Figure 1. This aircraft is in the large twin-aisle class, with a similar mission to a 777-200LR, and is referenced as the TW301 throughout the body of this paper. Addition of an M suffix indicates the Mid Term configuration prior to performing the roadmap, while an F suffix indicates the Far Term configuration. It is sized to transport 301 passengers over a maximum range of 7500 NM at a cruise Mach number of 0.84. Twin geared turbofan-like (GTF) engines are utilized to take advantage of the efficiencies offered by decoupling the fan and core rotation rates.

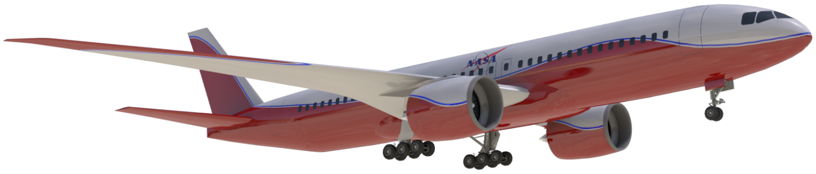


Fig. 1 An illustration of the conventional tube-and-wing architecture TW301M with engines under the wing is shown.

Extensive details outlining the aerodynamic design process for the baseline configuration's engine and airframe are provided in Nickol and Haller [2], while additional details of the past prediction of the baseline configuration certification noise is given in Thomas, Burley, and Nickol [6]. Since these publications, the airframe design has been further optimized, resulting in a slightly different planform, high lift design, and landing gear definition. This redesign changes the aircraft weight as well as the flight path. The propulsion system is the same as the previous assessment [2], and no changes to the engine sizing were required for the redesigned airframe. Aircraft parameters relevant to the noise prediction are summarized in Table 1, while the propulsion parameters are contained in Table 2.

Table 1 Relevant parameters are summarized for the TW301.

Dimension	Value	Units
Takeoff Gross Weight	555 001	lb
Wing Span	223.24	ft
Wing Loading	122.5	$\mathrm{lb\,ft^{-2}}$
Leading Edge Sweep	34	°
Takeoff Field Length	8841	ft

III. Noise Prediction Details

The metric that is used to assess the noise performance of each aircraft configuration is the cumulative certification noise. The noise certification process for large commercial transports is outlined in 14 Code of Federal Regulations Part 36 [7]. Upper limits for the received noise level at a ground observer location are established at each aircraft operating condition relevant for near-airport noise. A limit is also imposed on the cumulative noise summed over the three operating conditions: approach, full power departure (lateral), and departure engine cutback (flyover). The observer locations are shown in Figure 2, along with details of the process for determining the certification noise level metric, the effective perceived noise level (EPNL). This metric attempts to incorporate factors that contribute to noise annoyance. Duration is accounted for by integration of the time history of the tone corrected perceived noise level (PNLT), which in turn accounts for noise amplitude, spectral character, and the nonlinear sensitivity of the human ear.

In order to predict the certification noise levels for each of these aircraft, the NASA Aircraft NOise Prediction Program (ANOPP) is utilized. This program models each of the aircraft noise sources and propagates the source noise to an observer location as the aircraft flies along a flight path. Care is also taken to include propulsion airframe aeroacoustic (PAA) effects to account for interaction effects on the source noise level and directivity.

A. Noise Prediction Modeling

As mentioned previously, the research version of ANOPP L31v6 is utilized, running within the ANOPP2 framework [8] to predict the noise of the TW301. The research version contains several additional noise source prediction methods that are not available in the publically released version of ANOPP. An overview of the noise prediction process for the TW301 is shown in Figure 3. This process begins with the definition of the aircraft design. The design process consists of engine design using the Numerical Propulsion System Simulation (NPSS) tool [9],

Table 2 Engine parameters are summarized for the TW301.

Dimension	Value	Units
SLS Thrust per Engine	74 000	lb
Fan Diameter	12.6	ft
Number of Fan Blades	16	
Number of Stator Blades	36	
Normalized Rotor-Stator Spacing	1.52	rotor chord
Fan Pressure Ratio	1.25	
Bypass Ratio	23.27	
Departure Fan Tip Mach Number	0.91	
Approach Throttle Setting	17	%
Flyover Throttle Setting	76.9	%
Lateral Throttle Setting	100	%
Inlet Lined Length	0.67	R
Interstage Lined Length	0.2	H
Aft Lined Length	1.57	H

coupled with airframe design using the FLight OPtimization System (FLOPS) [10]. This aircraft design process also requires low speed aerodynamic performance estimates, obtained from a Modified Vortex Lattice (MVL) tool [11], to inform the flight path design. This leads to the complete geometric design and engine state required for noise prediction. Using this information, source noise predictions of nearly all elements are handled within ANOPP using models, ranging from empirical to physics-based approaches. However, some effects are handled externally with additional software and passed to ANOPP to complete the noise prediction. These include source predictions based on experimental data, PAA effects, and the impacts of technologies on the source noise.

For the TW301, the three main engine source elements are considered: the fan, core, and jet. The engine noise is predicted using experimental data [12] obtained during ERA, scaled for the appropriately sized engine. It is imported into ANOPP using the ACoustic Data module (ACD). The effects of the acoustic liner are predicted using the LINER module, which is a modified version of the GE TREAT model [13]. The core noise is computed using the GECOR module [14], and the updated version [15] of the Stone model, ST2JET, is used to estimate the jet noise. The airframe comprises the prediction of four source elements: the landing gear, trailing edge, flap side edge, and leading edge Krueger. The baseline configuration, which corresponds to the previously published results for this aircraft [6], uses several airframe prediction methods that have been recently updated. In that work, the Boeing AirFrame (BAF) prediction method [16, 17] was utilized to predict the flap side edge noise, while the landing gear and Krueger noise were predicted using early versions of the Guo models [18, 19]. Updated versions of the Guo models with several minor modifications are used for landing gear and high lift system noise in the present work. The prediction of the interaction effects between the landing gear and flap was also decoupled from the landing gear source noise prediction, so that each can be predicted as needed. An unpublished prediction model by Guo following a similar framework was used to predict the flap side edge noise. In both the current and past prediction, the trailing edge noise is predicted using the Fink model [20].

Following the source noise prediction, suppressions are applied to account for a variety of effects and technologies. Figure 3 shows some of the main technologies and effects that are included in the baseline configuration with Mid Term technology assumptions. With the modified source noise levels and directivity, as well as the flight path, ambient conditions, and observer locations, the source noise can be propagated to the ground. Following this propagation, noise metrics can be computed from the acoustic pressure time history at the observer.

B. Propulsion Airframe Aeroacoustic Effects

Interactions between the propulsor and the airframe can be important in properly predicting the noise performance of a particular configuration. Two approaches have been taken toward prediction of PAA effects, computational-based and data driven. The most common computational-based approach for use in system noise is a ray tracing approach

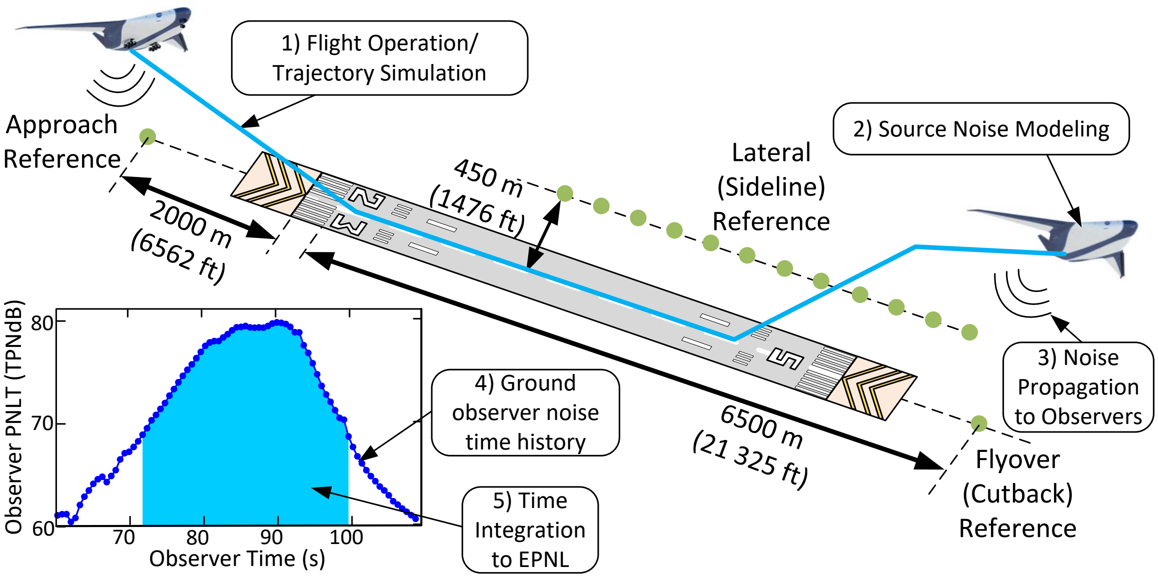


Fig. 2 The location of the certification points along with an overview of the process of obtaining an EPNL from a prediction.

based on the Kirchhoff Integral method [21–23]. This method is well suited to the needs of a system noise assessment due to the low computational cost. However, this reduction in computational requirements is accomplished through several assumptions and approximations that neglect some of the physics of the problem. The data driven approach, which is used in this paper, relies on experimental measurements of PAA effects, and, by its nature, includes all of the problem physics, albeit at model scale.

The experimental database used for the TW301 is based on extensive wind tunnel tests in the Boeing Low Speed Aeroacoustic Facility [24, 25]. For a portion of the test, acoustic measurements were taken for two isolated noise sources, a jet noise simulator, and a broadband noise source that was installed in a nacelle, shown in Figure 4. To capture the directivity effects, measurements were taken using three polar arc microphone arrays each placed at different azimuthal angles. Measurements were also taken for both sources when integrated with a scaled model of a 777 airframe. Although additional data were taken with a hybrid wing body airframe as seen in Figure 4b, only the scaled 777 airframe data are used in this paper. Data were taken at several freestream Mach numbers and flap settings as the relative placement of the noise source and airframe was varied. This allows for the estimation of the PAA effects for a variety of aircraft operating conditions. There are several advantages to the data driven approach, namely the inclusion of the full physics of the acoustic scattering, and inclusion of propagation through mean flow and airframe model shear layer. The sources are also more realistic than those typically used in the computational approach, allowing for a better approximation of the complex directivity of real jet and broadband fan noise.

These data have been used in several previous studies to estimate the impact of engine shielding and reflection [6, 26–28]. The general approach is to choose the experimental test point that matches the flow variables and relative placement of the engine noise source and the airframe as closely as possible to the conditions that are seen on the full scale aircraft. No interpolation between test points is performed. The suppression due to the PAA as a function of frequency and directivity can then be computed from the particular installed (shielded) and isolated test point sound pressure levels,

$$\mathcal{S}(f,\theta,\phi) = \frac{p_i^2}{p_f^2} = 10^{\frac{L_i - L_f}{10}}. \tag{1}$$

The frequency dependence of the suppression function is transformed from model to full scale via Strouhal scaling based on the nozzle diameter. The absence of angular dependency in the transformation implicitly assumes that the wing planform of the TW301 is a scaled version of the 777 wind tunnel model wing planform. For the TW301, several

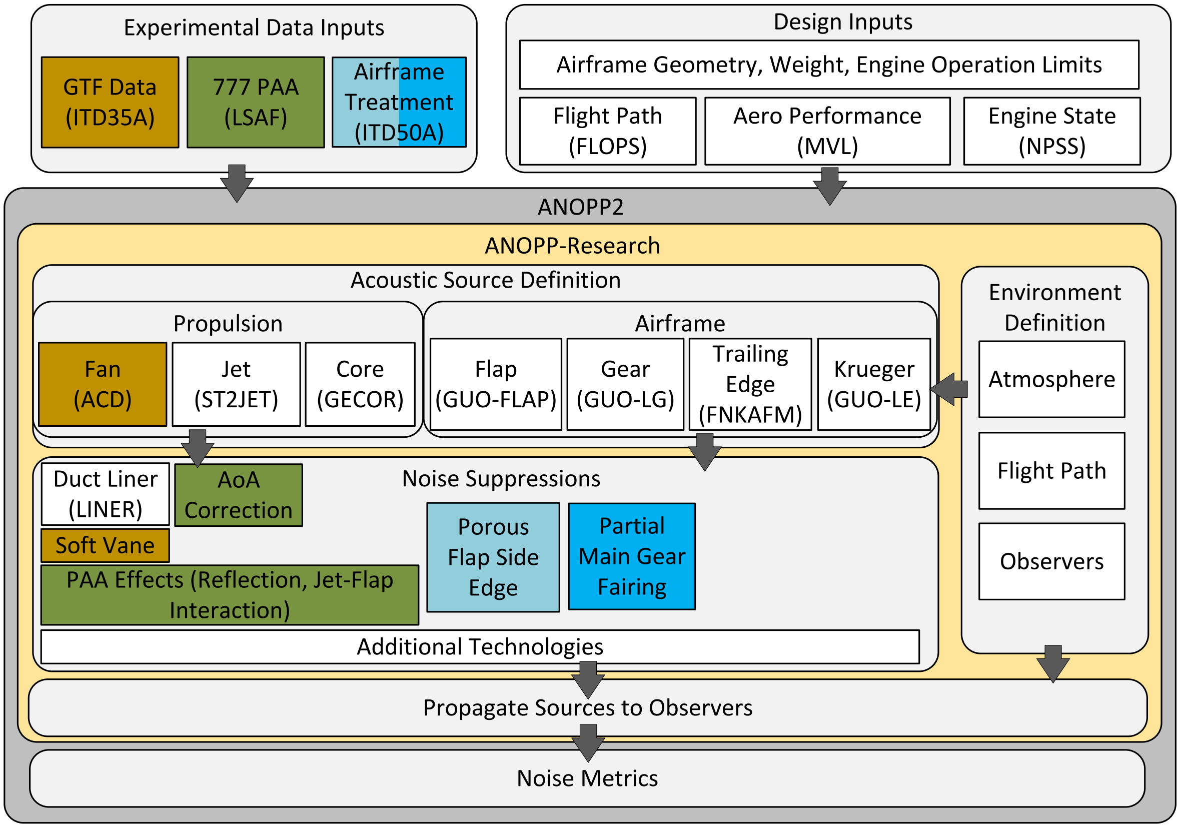
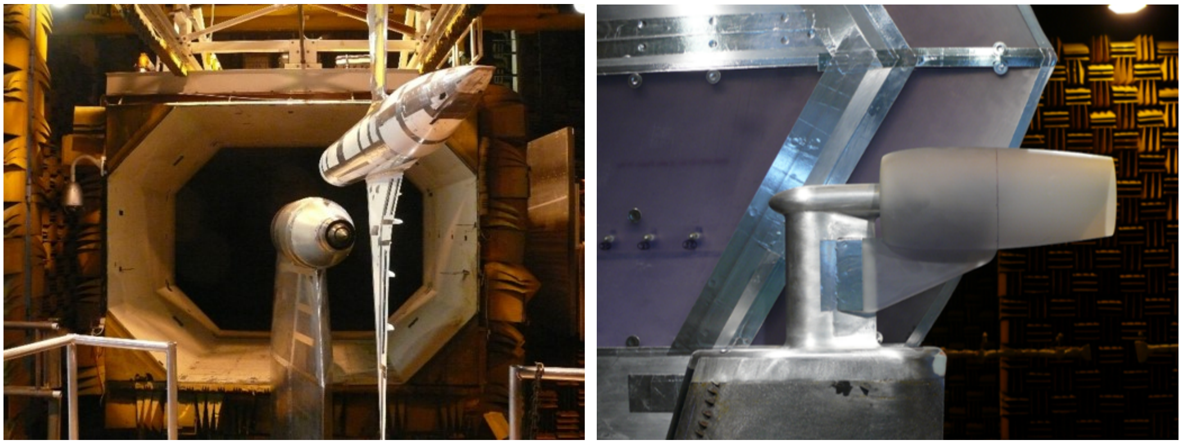


Fig. 3 The overall data flow for the noise prediction is shown. The heritage of the data is shown through consistent coloring. Suppressions are applied to the source modules above them. Names of the software or ANOPP modules used to generate the prediction are given in parentheses.

PAA effects are present that must be taken into account. As was mentioned previously, data are available to model the source noise changes due to reflection from the wing for both a broadband source emanating from a nacelle, and a distributed jet source. In the past assessment, only the reflection of the fan and core noise was included in the analysis through use of the broadband source. This was due to the dominance of the fan noise relative to the other elements. For completeness, the effect of jet reflection is included as well. Additionally, due to the integrated nature of the test, the jet reflection map also includes the impact of jet-flap interaction noise. The suppression functions for the fan and core, as well as the jet noise on departure are shown in Figure 5 at the full scale frequency of 1 kHz. Separate suppression functions are used for the departure and approach certification conditions.

IV. Mid Term Results and Far Term Technology Roadmap

Before presenting the technology roadmap, it is necessary to update the starting point at the Mid Term technology level. As mentioned previously, several prediction improvements and aerodynamic configuration changes have been made since the previous assessment of the TW301M [6]. These modifications have been discussed at length in previous sections as well as publications [4, 29], and are only listed here for completeness. Several changes have been made to the modeling of the acoustic liners based on updates to Mid Term technology assumptions. The effects of swirling flow are accounted for in the interstage by reducing the effective lined area by a factor of two. The acoustic lining added to the bifurcation is modeled by increasing the total aft liner area by the amount of treated area on the bifurcation, and does not account for any of the physical effects that the bifurcation has on the modal content in the aft duct. This assumption was made due to limitations in the framework of the current acoustic liner prediction method. The multiple degree of



a) b)

Fig. 4 Images of the integrated test of a scaled a) jet noise source and 777 airframe, and b) fan broadband noise source and hybrid wing body are shown.

freedom acoustic liner modeling has also been updated to more accurately capture the spectral shape of the absorption. The atmospheric absorption method has been updated to use the SAA866A standard [30], as this is the absorption method specified in regulations for aircraft noise certification. Last, the PAA effects of reflection of jet noise from the underside of the wing to the ground have also been incorporated into the prediction.

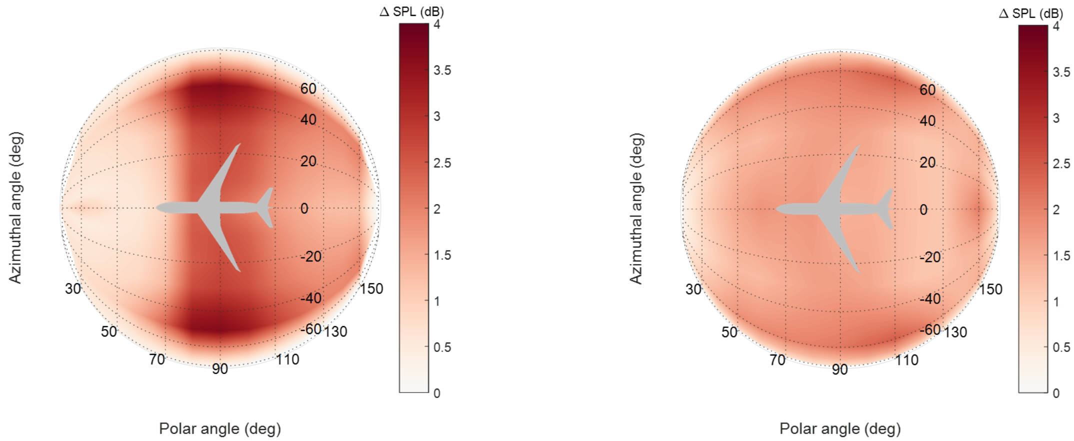
Following application of the above configuration changes, the certification noise is predicted for the TW301M. Results of the updated prediction are shown in Figure 6 for each of the three certification points. From this figure, it is clear that the most benefit can be gained by noise reduction technologies that address the fan noise. After the fan noise, the leading contributors at approach are the main landing gear and the high lift system. At flyover, the core and Krueger are the next most important sources, while at the lateral condition, the remaining engine noise sources provide the best target for overall noise reduction.

After surveying literature for noise reduction technologies and including several NASA-developed technologies, a subset of technologies deemed suitable for addressing the given aircraft source ranking balance is included in the Far Term roadmap for the TW301. These technologies are detailed in the following two subsections.

A. Engine and PAA Noise Reduction

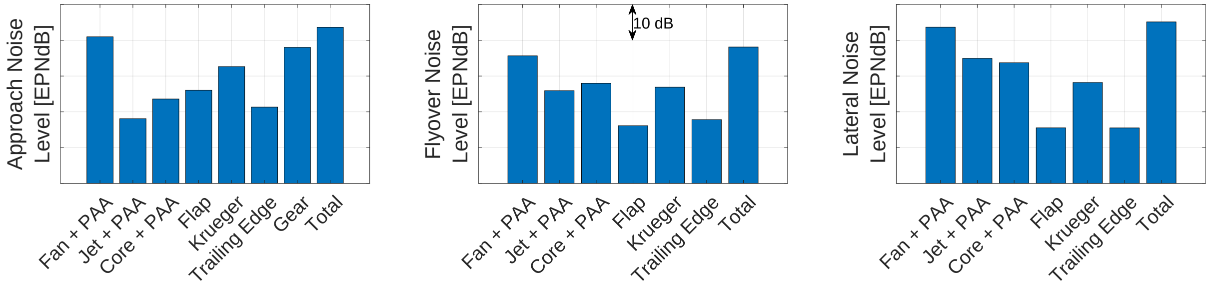
Several technologies are being matured to address engine noise reduction. As is clear from the source rankings, focus on the engine noise sources, particularly the fan, is required to effectuate a substantial reduction in the system noise. One strategy for the fan is to more efficiently use the surface area in the engine nacelle to increase the treated area. This can mean either integrating acoustic liners in nontraditional locations, or purposefully increasing the available area for treatment inside the nacelle. One technology that has received attention in the past decade is the application of an inlet liner that extends all the way to the leading edge of the nacelle. This has been tested both at model scale [31] and in flight [32]. Based on the NPSS engine design, use of a lip liner increases the treated inlet length by 25 %, which is used as an input to the LINER module. Work on over-the-rotor (OTR) liners has also shown promise for reducing fan noise [33, 34]. Based on data from these previous publications, a uniform suppression with respect to frequency and emission angle is developed and applied at all three certification points. Additionally, a thickening of the upper bifurcation is considered to increase the amount of aft area. However, doing so only increases the effective L/H in the aft duct by 3 %.

To treat core noise, an acoustic liner is placed in the centerbody of the core exhaust. This has been shown to be quite effective in a static engine test [35], with an 8 dB SPL reduction at the peak frequency and directivity angle. A suppression map with a narrowband reduction with a strong spectral roll-off is applied with the same peak reduction to the TW301. The test data are from a CF34-10E, which is sized for a regional jet. The additional space available within the much larger TW301 engine allows for the assumption of the same peak reduction as well as a slight shift in frequency of the attenuation spectrum to align with the peak of the TW301 core noise. The results of Yu and Chien [35] appear to show a reduction of the effectiveness of the center plug liner at higher engine power settings. However, Martinez [36]



a) **b)**

Fig. 5 A comparison of the suppression functions (Equation 1) at departure conditions is shown for a full scale frequency of 1 kHz for the a) fan and core, and b) jet sources. Positive values indicate an increase in the noise radiated to the ground.



a) **b)** **c)**

Fig. 6 The ranking of the sources is shown for each of the TW301M certification point predictions relative to an arbitrary reference value. Approach, flyover, and lateral are shown in a), b), and c), respectively.

shows in further analysis of the same static engine test that this is due to an increased noise floor for the measurements from jet noise. For this reason, the same suppression is applied to all engine power settings.

One application of acoustic liners external to the engine nacelle is also incorporated in the roadmap. This concept stems from the application of a PAA acoustic liner in Czech and Thomas [25] to a hybrid wing body planform in an effort to increase the effectiveness in shielding the dorsal-mounted open rotor propulsors. However, in this case, an acoustic liner is placed on the underside of the wing to reduce the aft reflection from the engine. The treated area is envisioned to cover the pylon and the wing from the bypass duct exit to trailing edge in wing chord, and over the span of the engine. This relatively limited application was chosen due to the increase in drag associated with a lined surface. However, recent work [37] indicates that the drag penalty can be at least partially mitigated through changes to the perforated sheet exposed to the flow. Modeling for the concept is preliminary, and no detailed analysis has been performed. For this reason, the assumed effectiveness of the liners is quite conservative. The reflection from the fan and core shown in Figure 5b is modified over a frequency range of 1–2 kHz to reduce the reflected rays by half on a pressure-squared basis. This frequency range was targeted based on the fan source spectrum, the relative importance to annoyance, and depth constraints for feasibly integrating a quarter wavelength resonator into the wing. This reduction is further limited to aft polar emission angles and azimuthal angles within 30° of the overhead flight path.

Last, a negatively scarfed inlet is implemented in order to change the directivity of the inlet fan noise. This concept has been applied in a static fan rig test [38], as well as simulation and flight [39] where it showed the ability to effectively reduce fan noise. Based on unreported data from a past wind tunnel test [24], a suppression map is developed for the scarfed inlet. The noise from a broadband noise source in isolation as well as within a scarfed nacelle is measured using three polar arc microphone arrays. The difference between the noise levels is used as the basis for the suppression map. The scarfed nacelle in the wind tunnel test was hardwalled, and the impact of having additional surface area from the elongation of the lower half of the nacelle is not included here but is likely to increase the effectiveness of the treatment if this is accounted for in future work.

B. Airframe Noise Reduction

Technologies are also applied to key airframe noise sources. For the main gear, changing to a four wheel main gear bogie from a six wheel gear was considered. The six wheel gear was chosen to match the gear of the 777-200LR reference vehicle for this class. However, Mid and Far Term structures technology assumptions reduce the weight of the TW301 to the point where a four wheel gear is feasible. A more detailed rationale and examples of production aircraft with similarly sized main gear are given in Guo et al. [3]. A partial nose gear fairing (PNGF), the same technology applied to the main gear for the Mid Term configuration, is incorporated in the roadmap with the expectation that reduction in other components may allow nose gear noise reduction to have an impact at the system level. For the leading edge Krueger flap, a dual use fairing (DUF) is proposed [3]. This fairing covers both the Krueger cavity and the brackets, greatly reducing the noise generated by these components and in turn, the overall noise of the Krueger flap element. The impact of sealing the gap between the trailing edge of the Krueger flap and leading edge of the wing on approach is also considered. To address flap side edge noise, a continuous moldline link (CML) flap architecture is considered. This greatly reduces the flap side edge noise by removing any discontinuities in the trailing edge due to flap deployment [40]. When applied, this technology replaces the porous flap side edge treatment that has been applied for the Mid Term vehicle concept.

C. Roadmap Procedure

In prior studies [3, 4], the technologies included in the roadmaps were applied incrementally in a preset order until reaching the Far Term configuration. In the initial roadmap, the technologies were grouped into those with high and low technology readiness levels. To compare all the technologies on a equivalent basis, a “one-off” analysis was performed in which each technology was removed independently from the final aircraft configuration. While all of the technologies discussed here could be developed in the given timeline, it is possible that some technologies will not be matured or included in a future production vehicle. If decisions to mature technologies are based on the criteria of noise reduction potential via a one-off analysis, it must be assumed that each technology on the Far Term configuration (with all other technologies applied) has the same value on the baseline Mid Term configuration.

The primary focus of these initial roadmaps is to identify any weaknesses in the current portfolio of technologies so that future roadmaps can provide a more robust path to reaching NASA noise goals for each architecture. However, attention is also given to the manner in which the buildup occurs. The order in the buildup to the Far Term configuration is dictated by the noise reduction potential of each technology. A new process was developed, which is termed an iterative one-on procedure, that evaluates a much larger number of technology combinations. The result is a more informative roadmap study that reveals ranking dependencies between technologies while also identifying those technologies that can be of most use when applied alone. The process begins by considering all of the candidate technologies to be evaluated; a given technology is incorporated into a noise prediction in ANOPP, the cumulative noise metric is calculated, and the technology is removed before the next technology is considered. Once all candidate technologies have been considered, the most effective technology (the one leading to the greatest reduction in cumulative system noise) is selected to represent the first step in the roadmap, completing the first iteration of the roadmap process. During subsequent iterations, the remaining candidate technologies are applied separately from each other, but in conjunction with the technologies chosen during the previous iterations. Naturally, the final iteration of this procedure includes all technologies in the roadmap in addition to the final candidate technology. The resulting cumulative noise metric computed therefore represents the minimum noise level achievable, with all noise reduction technologies applied.

Table 3 shows an example of this process for three technologies on an arbitrary configuration. During the first iteration, each of the three technologies are all evaluated independently. Tech 2 is seen to be the most effective and is chosen for the first step of the roadmap. During the second iteration, the Tech 1 and 3 are separately evaluated while retaining the effect of Tech 2; Tech 1 is chosen next. For the final iteration, Tech 3 is applied together with Techs 1 and 2, where it is selected as the final technology (by default).

As illustrated in Table 3, the system-level impact of the technologies is generally not static throughout the process. As technologies are applied throughout the process, changes in source ranking lead to changes in a technology’s value at

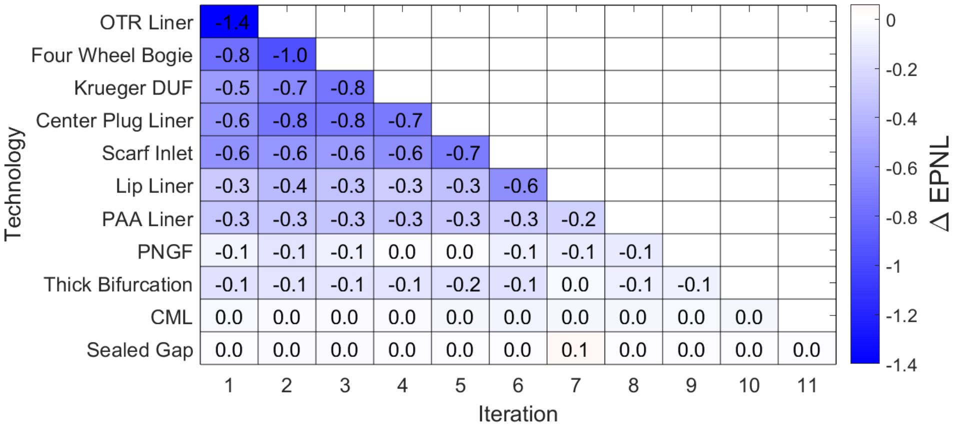
Table 3 An example of iterative one-on roadmap procedure. Values shown here are changes in overall system-level EPNdB calculated and summed over all certification points, but are for illustration purposes only.

		Candidate Technologies		
Iteration	Roadmap Technologies	Tech 1	Tech 2	Tech 3
1	None (baseline)	−0.9	**−1.6**	−0.5
2	Tech 2	**−0.7**	——	−0.6
3	Tech 2, Tech 1	——	——	**−0.6**

the system level. This process helps to answer questions related to technology development that will become more important as the portfolio and modeling of available technologies becomes more robust. Following completion of the iterative one-on procedure, a one-off analysis identical to those performed in prior studies is again completed as a final step. This evaluates the importance of each technology to the final, quietest configuration. Again, the effectiveness of each individual technology will be slightly different between one-off and one-on, depending on the relative differences in the source ranking between the two configurations.

V. TW301 Results

Using the iterative buildup procedure discussed in the previous section, all of the technologies described in Sections IV.A and IV.B are applied to the Mid Term TW301 configuration. The relative impact of including the technologies on the cumulative certification noise level is shown in Figure 7. Each column corresponds to an iteration where the impact of adding each individual technology is predicted in turn. Moving left to right on the plot through the process, the technology providing the largest reduction in cumulative noise is permanently retained as part of each interim configuration. As the technologies are permanently added to the interim configurations, they are no longer considered in the iteration process, resulting in the empty upper triangular portion of the plot. For convenience, the technologies are ordered top to bottom to match the iteration in which they were chosen, such that the largest noise reduction case for each iteration is shown on the major diagonal.

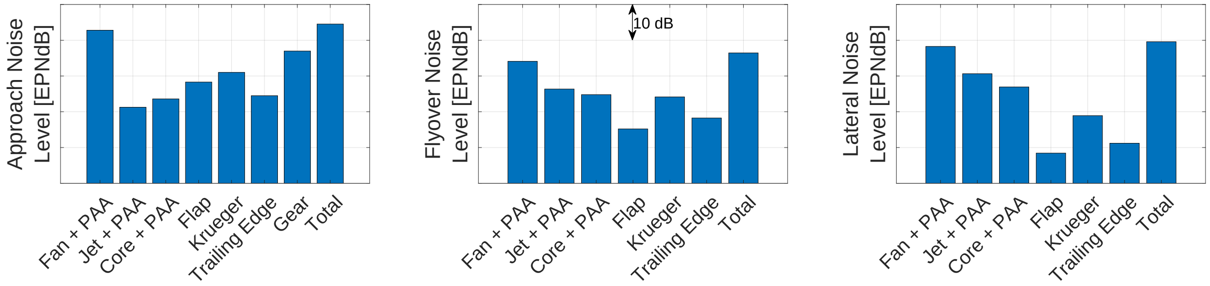


Technology	1	2	3	4	5	6	7	8	9	10	11
OTR Liner	-1.4										
Four Wheel Bogie	-0.8	-1.0									
Krueger DUF	-0.5	-0.7	-0.8								
Center Plug Liner	-0.6	-0.8	-0.8	-0.7							
Scarf Inlet	-0.6	-0.6	-0.6	-0.6	-0.7						
Lip Liner	-0.3	-0.4	-0.3	-0.3	-0.3	-0.6					
PAA Liner	-0.3	-0.3	-0.3	-0.3	-0.3	-0.3	-0.2				
PNGF	-0.1	-0.1	-0.1	0.0	0.0	-0.1	-0.1	-0.1			
Thick Bifurcation	-0.1	-0.1	-0.1	-0.1	-0.2	-0.1	0.0	-0.1	-0.1		
CML	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
Sealed Gap	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0

Fig. 7 The cumulative system level impact of each technology, given in units of ΔEPNdB, is shown for the iterative buildup of the Mid Term configuration to the Far Term.

Several things are apparent from the results of the iterative one-on procedure, which can all generally be explained by the ranking of the aircraft noise sources. The first is that several technologies are ineffective throughout the entire roadmap procedure, namely the PNGF, thickened bifurcation, CML, and sealed Krueger gap on approach. The impact of the PNGF and sealed Krueger gap are limited since they only influence the approach certification point. Additionally, they target minor elements with respect to the source balance. The PNGF is quite effective at reducing the nose gear level on approach by 2 EPNdB, but this is lost due to the element's importance at the system level. Similarly, the CML effectively reduces the flap level by 5 EPNdB on the cumulative component level. This indicates that for the TW301 considered here, the porous flap side edge treatment present on the Mid Term configuration provides sufficient noise reduction for the flap until the major noise sources, namely the fan noise, can be reduced. Unlike the other ineffective technologies, the thickened bifurcation treats fan noise, the principal contributor to the system noise. For this case, the limiting factors are the small overall amount of lining that is added to the aft duct as a result of expanding the bifurcation liner, and the simplification in modeling of the bifurcation effect as an additional treated area.

As mentioned in Section IV.C, technology values are expected to vary at different iterations as the relative source ranking changes. However, the technology mix applied to the TW301 in the Far Term roadmap fails to balance the source levels, shown in Figure 8, even though half of the technologies target fan noise. Only the ranking order of some of the secondary sources has changed due to the application of several technologies that are effective at the element level. Despite this limitation, some technology impacts do show variation throughout the process. The clearest example of this is the doubling of the noise reduction potential of the lip liner following application of the scarfed inlet. The scarfed inlet changes the fan directivity in such a way that the lip liner is more effective. An additional effect that is not currently included in the analysis is the increase in lined area from lengthening the lower half of the nacelle inlet.



a) **b)** **c)**

Fig. 8 The ranking of the sources is shown for each of the TW301F certification point predictions. Approach, flyover, and lateral are shown in a), b), and c), respectively.

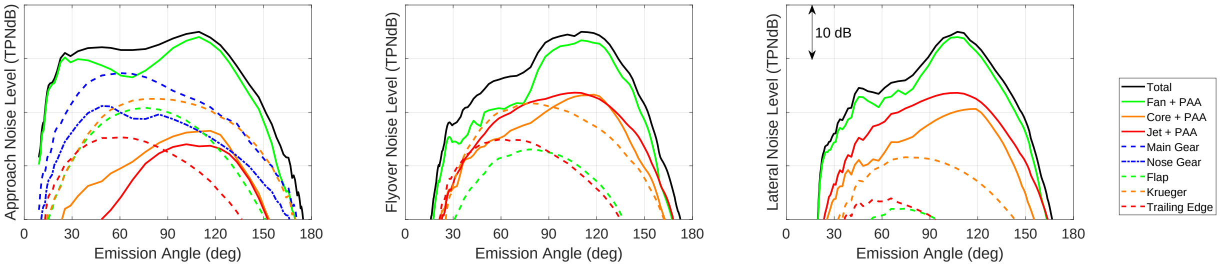
To facilitate additional analysis at the system level, the results of the interim roadmap configurations on the main diagonal of Figure 7 are recapitulated in Table 4 along with the Mid and Far Term configuration results. In addition to the noise reduction potential of each technology obtained by the iterative one-on procedure, the values obtained by removing that technology from the Far Term configuration in a one-off approach are also provided. The one-off analysis generally estimates a larger benefit for a given technology than the one-on analysis, particularly for the more effective technologies applied earlier in the roadmap. This highlights that the noise reduction potential of a technology is dependent on the specific source ranking of the baseline configuration. The cumulative noise margin relative to Stage 4 regulations is also shown for each configuration. The primary observation is that the cumulative noise margin of the TW301M is 24.3 EPNdB and 30.0 EPNdB for the TW301F, which falls short of both the Mid Term (32–42 EPNdB) and Far Term (42–52 EPNdB) NASA goals [1]. Even further, the 5.6 EPNdB of noise reduction obtained from the roadmap, representing an additional decade of technology development, indicates it is unlikely that the TW301 will even be able to reach the Mid Term goal in the Far Term time frame. None of the technologies showed a significant reduction in noise, and only two technologies reduce the cumulative system noise by more than 1 EPNdB in both the one-off and -on analyses. This modest reduction exposes the need to mature additional technologies suitable for treating fan noise. As was seen in Figure 8, fan noise remains the primary source of noise at the system level for the TW301F.

More detailed information at the element level is helpful to clearly discern a strategy to improve the technology roadmap for the TW301 in future work. To this end, tone corrected perceived noise levels (PNLT) for each element are shown for the Far Term configuration at each certification point in Figure 9. Traditionally, the PNLT is shown as a function of time, as this is what is ultimately integrated to determine the EPNL. However, for the purposes here, it is helpful to transform the time dependency to the polar emission angle. Emission angle is relative to the outward normal from the nose of the aircraft. This makes it clearer that the specific challenge for the TW301 is the aft fan noise; inlet fan noise is only significant on approach. It is quite clear to see that other components only have a meaningful contribution to the total noise in the 45°–75° range by noting where the trend for the fan noise does not shadow the total aircraft PNLT.

The importance of fan noise to tube-and-wing aircraft has been known for some time. However, this roadmap

Table 4 The cumulative system level impact of each technology is given in units of ΔEPNdB in the chosen buildup order.

Technology	Element	Stage 4 Margin	One-On	One-Off
Mid Term	——	24.3	——	——
Over-the-Rotor Liner	Fan	25.7	−1.4	−1.6
Four Wheel Bogie	Main Gear	26.7	−1.0	−1.1
Krueger Dual Use Fairing	Leading Edge	27.5	−0.8	−1.1
Center Plug Liner	Core	28.2	−0.7	−0.9
Scarf Inlet	Forward Fan Directivity	28.9	−0.7	−0.8
Lip Liner	Forward Fan	29.5	−0.6	−0.5
PAA Wing Liner	Aft Fan/Core Reflection	29.7	−0.2	−0.3
Partial Nose Gear Fairing	Nose Gear	29.9	−0.1	−0.1
Thickened Bifurcation	Aft Fan	29.9	−0.1	−0.1
Continuous Moldline Link	Flap	30.0	0.0	0.0
Sealed Gap on Approach	Leading Edge	30.0	0.0	0.0
Far Term (Total)	——	30.0	−5.6	——



a) b) c)

Fig. 9 The tone corrected perceived noise levels for each of the Far Term certification point predictions are shown as a function of emission angle from the aircraft to the certification observers. Approach, flyover, and lateral are shown in a), b), and c), respectively.

makes clear that even with a technology mix that focuses on reducing the fan noise, other noise sources are unlikely to contribute significantly at the system level. For fan noise, there are three general opportunities to reduce the noise: at the source, interior to the nacelle, and on surfaces contributing to reflection of noise toward observers on the ground. Source noise reduction generally centers on changing the count, spacing, and geometry of rotor and stator blades, with some other work also investigating active noise control or blowing techniques [41]. Within the aft bypass duct, treating fan noise is typically accomplished through application of acoustic liners. Additional noise reduction could be obtained through more efficient acoustic liners. For example, interstage liners have been shown to have reduced effectiveness due to the presence of swirling flow [42]. Acoustic liners that have been shown to decrease their associated weight [43] and drag [37] penalties could be implemented to trade for a longer engine nacelle. Variable depth bent chamber acoustic liners are also being developed [44] to achieve broadband noise reduction with more efficient volumetric packing. Once out of the engine nacelle, it is seen from the application of the PAA liner in the technology roadmap that there can be some impact in the certification noise by reducing the strength of the reflection for this aircraft. From Figure 5b as well as discussion in Section VI, it is somewhat surprising that the PAA liner only offered a 0.3 EPNdB reduction in cumulative noise. There is a real opportunity for noise reduction with this technology since it targets the primary source of noise on the aircraft. It is likely that the modeling assumptions for the liner are conservative, and that with additional analysis, a more effective PAA acoustic liner could be designed.

VI. Comparison with Unconventional Architectures

There is also interest in comparing the relative acoustic performance of the TW301 with the unconventional concepts in the same class, the MFN301 [3] and HWB301 [4]. Each aircraft is designed for the same mission, uses GTF-like engines of the same design family, and is compared using equal technology assumptions. This set of aircraft presents an opportunity to more directly compare the noise impact of configuration change due to the different PAA effects of the aircraft. Table 5 shows the most recent prediction of the Mid Term technology level configuration of the three concept architectures with and without the prediction of PAA effects. This is equivalent to predicting the aircraft with installation effects and as an incoherent summation of each isolated element of the aircraft. The benefit is computed as the difference between the two predictions. The impact of the HWB301 and TW301 was assessed previously [6], but there was not an equivalent MFN considered in that study.

Table 5 The impact of PAA effects on Mid Term twin-aisle concepts is given in units of ΔEPNdB.

Concept	Margin with PAA	Margin without PAA	PAA Benefit	Previous Prediction[6]
TW301	24.3	28.6	−4.3	−4.8
MFN301[3]	34.4	30.2	4.2	——
HWB301[4]	40.4	34.0	6.4	7.1

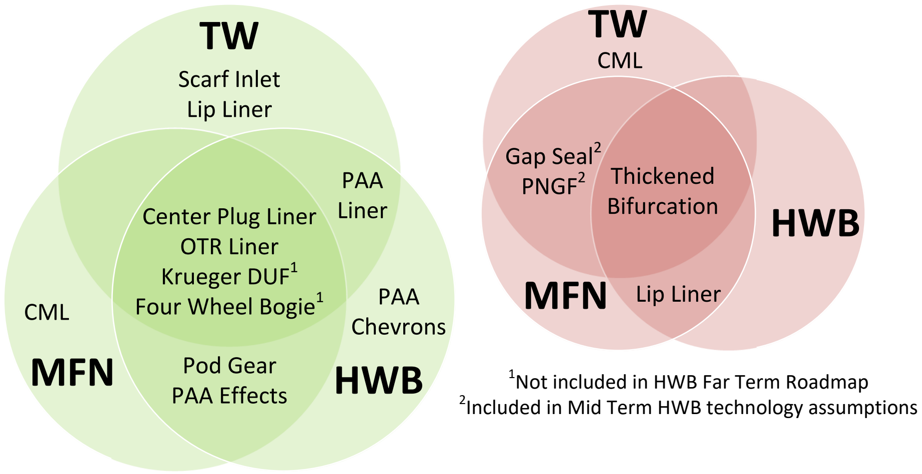
It is estimated that there is an 8–10 EPNdB benefit of unconventional architectures with favorable PAA effects relative to the conventional tube-and-wing design. It is important to note that the PAA effects are not the only differentiators between the three aircraft concepts, i.e., they do not have the same certification noise margin when flown as a collection of isolated noise sources. Other factors like flight path, weight, and sizing also impact the noise reduction potential of the three concepts. However, this result highlights the importance of PAA effects as a substantial opportunity to increase the noise reduction potential of an aircraft architecture. Interestingly, the MFN301 is able to capture the majority of the benefit of an unconventional engine-airframe integration, and presents a lower risk unconventional option that does not diverge completely from decades of experience building tube-and-wing aircraft. Changes in certification noise believed to be related to the integration of the engine and airframe have been noted before [28], where a 5.6 EPNdB difference in certification noise was noted for an MD-90 with tail mounted engines compared to an A319 with the same engine and similar gross aircraft sizing.

The result here is specific to the three configurations shown. While the PAA benefit of these configurations should correlate well to different configurations of the same aircraft architectures, some engine parameters are likely to influence the magnitude of the benefit. The BPR of the engine will result in changes as to the relative rank ordering between the fan and jet noise. The BPR of the three configurations here is on the order of twenty. The results may change at lower bypass ratio where aft shielding may become less effective due to a relative increase in the jet noise. This may also strengthen the jet-flap interaction for engine-under-wing configurations. Similarly, changes in the fan pressure ratio will have an effect on the relative importance of inlet and aft fan noise, corresponding to more or less importance in inlet and aft shielding or reflection. The relative ranking between engine noise sources and airframe sources can also play a role, where airframe noise may provide a ceiling for the PAA benefit if the engine noise sources are substantially shielded.

Results of the PAA impact are not shown for the Far Term concepts. Technologies are added to the roadmap based on each Mid Term configuration's source ranking and underlying PAA effects. Several Far Term technologies directly change the PAA effects (e.g., TW301 PAA liner), rely on them to be effective (e.g., HWB301 PAA chevrons), or can only be used on an unconventional configuration (e.g., pod gear [45]), confounding the decision as to which technologies should be included when assessing the impact of the PAA effects. Analysis of the Far Term PAA impact has similar values as the Mid Term results shown when only the same shielding, reflection, and diffraction effects were removed.

It is also helpful to review which noise reduction technologies were successful at the system level and those that were not across the three completed Far Term technology roadmaps. Figure 10 shows two Venn diagrams of technologies; the green on the left indicates technologies that have strong noise reduction potential, while the red on the right indicates roadmap technologies that did not result in noise reduction for one or more configurations. It is important to note that the noise reduction technologies considered here span a wide range technology readiness level, and caution should be taken when drawing conclusions. One of the primary purposes of this comparison is to draw attention to technologies that may be beneficial but have not yet been significantly matured or tested.

Several technologies are beneficial for all three configurations, namely the center plug liner, OTR liner, Krueger DUF, and four wheel bogie. First, it is noted that the Krueger DUF and four wheel bogie were not technologies that



[1]Not included in HWB Far Term Roadmap
[2]Included in Mid Term HWB technology assumptions

Fig. 10 Two Venn diagrams showing the overlap of effective technologies (left) and ineffective technologies (right) for the three twin-aisle Far Term roadmap configurations are given.

were implemented in the HWB roadmap. However, precursors to the Krueger DUF in both a Krueger cove filler and bracket alignment with the flow were included. These treat the same noise sources as the Krueger DUF and were shown to be effective at the system level. Similarly, for the four wheel bogie, the pod gear technology showed promise for reducing the main gear noise. It is also noted that main gear noise is the primary source of noise on approach for the HWB301F, so it is likely that reducing the number of wheels would be helpful even after the pod gear has been applied.

Other technologies were only beneficial to two configurations. As has been mentioned before, the unconventional configurations gain an advantage in noise reduction potential not only from shielding, but also from technologies that the reconfiguration allows, such as the pod gear. Tailoring the PAA effects through an acoustic liner placed external to the engine nacelle reduced the noise for both the HWB301 and TW301. Some technologies had more mixed results. For instance, although CML is an effective technology at the component level, it does not have an impact at the system level for the TW301, while for the MFN301, the forward fan noise is reduced to the point that this change in the flap noise level impacts the system noise. A similar situation occurs for the lip liner, which is ineffective on the unconventional configurations due to their forward fan shielding, but effective on the TW301, which does not have inlet shielding.

It is also clear that the purposeful thickening of the bifurcation does not result in enough additional acoustic lining to significantly reduce the fan noise for any of the configurations, at least under the assumption that the effect can be modeled as a simple addition of liner area. It is likely that the partial nose gear fairing is also not effective at the system level for any of the aircraft, but due to the unique noise ranking of the HWB301, airframe noise was expected to be important, and it was included in the HWB301M. Even for the HWB301F, the peak nose gear PNLT is well below the total system noise, and the weight of the partial gear fairing would realistically be traded for the weight reduction. Sealing the gap on approach was also shown to have little benefit to the MFN301 and TW301. Due to differences in high lift requirements, the Krueger gap was sealed on approach for the HWB301M and was not part of the roadmap. It is more likely to be of some noise reduction value for the HWB301 since the Krueger is an important noise source at all three certification points.

The final comparison between the three aircraft is to consider the noise reduction potential of the aircraft in the context of historical values as well as NASA Mid and Far Term noise goals. In Figure 11, the cumulative noise margin for several twin-aisle production aircraft and predicted concepts is shown as a function of their entry into service (EIS) year. Different colored zones indicate the applicable noise regulations in effect over time. Cumulative margins for each aircraft are referenced to the regulations in effect when the aircraft entered service. Future aircraft concepts' cumulative margins are relative to the current regulations, Stage 5. Given the historical progression of more stringent noise requirements over time, it is likely that an additional generation of noise restrictions may be applied near the same time frame as the the Far Term concept EIS. Historically, this reduction has been between 7–10 EPNdB.

The historical data show that aircraft typically have a cumulative margin of 5–20 EPNdB, with lower margins

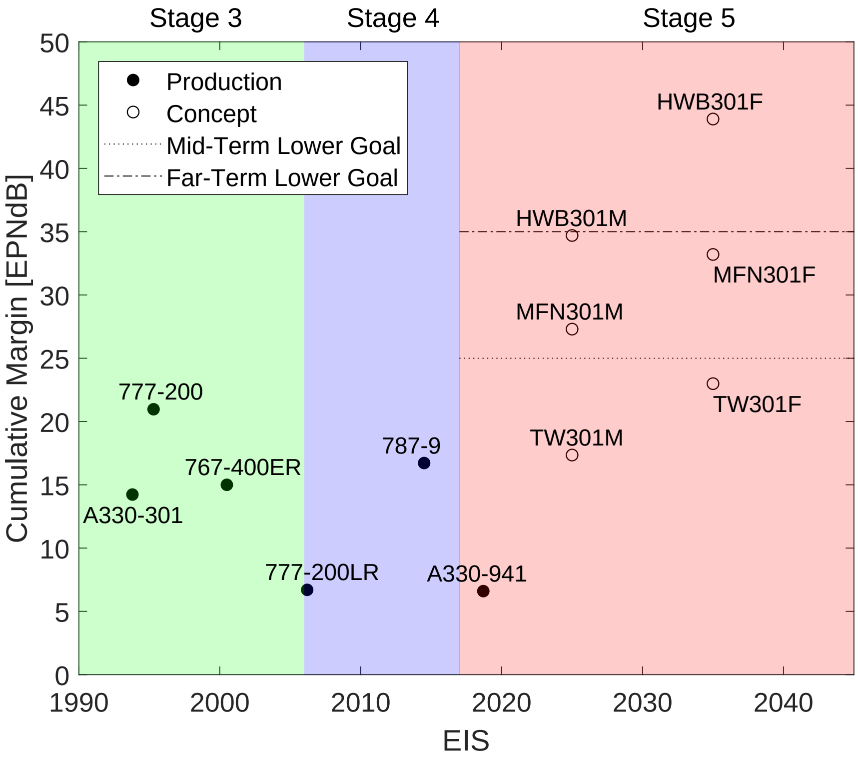


Fig. 11 The certification margins for several production aircraft and predicted concepts are shown as a function of entry into service (EIS). Colored zones show the applicable range of EIS dates for each noise regulation stage. Mid and Far Term concepts are denoted by the M and F suffixes.

occurring after a change in regulations. The TW301M is near the upper range of this historical trend, with a 17.3 EPNdB margin to Stage 5. The TW301F is above this range, but it is more on par with previous aircraft when accounting for historical trends in changes to noise regulations. This shows that there is still a path to incrementally maturing conventional architecture aircraft until at least the 2035 time frame. However, it is also clear that the TW301 falls short of both the Mid and Far Term NASA goals by a considerable amount. The MFN is able to meet the Mid Term goal and falls just short of the Far Term goal. With respect to the HWB301, it very nearly reaches the Far Term lower goal, which is also the Mid Term upper goal, in the Mid Term time frame. As is clear from Table 5, almost all of the difference between the TW301M and MFN301M is due to the configuration change of placing the engines above the wing. This clearly shows the most promising noise reduction technology for the TW301 is a reconfiguration for more beneficial PAA effects.

VII. Conclusions

A noise reduction technology roadmap has been developed to assess the potential of the TW301 concept in reaching the NASA Far Term noise goal. The TW301F has a cumulative margin to Stage 4 of 30.0 EPNdB, which even falls short of the Mid Term lower goal in the Far Term time frame. The primary reason for this shortfall is the lack of favorable PAA effects present for this architecture. This disadvantage is further increased as the wing reflection augments the primary source of noise, the aft fan, causing a 4.3 EPNdB increase in the cumulative system level noise. These are challenges for conventional aircraft operating today, and confirms that the issues are unlikely to be resolved by the Far Term time frame without an architecture change. This change in architecture could offer an 8–10 EPNdB reduction in cumulative certification noise.

Contrasted with the value of configuration change, application of the eleven technologies in the roadmap for the TW301 resulted in only 5.6 EPNdB of noise reduction. This limited impact highlights the need to develop additional technologies to further reduce aft fan noise, as well as the corresponding installation effects, and strengthen the portfolio of noise reduction technologies. Additional technologies are expected to reduce fan noise through source noise reduction, additional in-duct treatment, and tailoring of the PAA effects on fan noise. The four most effective technologies for the TW301, the over-the-rotor liner, four wheel main gear bogie, Krueger dual-use fairing, and center plug liner were also effective for the MFN301 and HWB301. Focused development of technologies that have a system level benefit for multiple architectures ensures that noise reduction research can make an impact regardless of which aircraft architectures are ultimately manufactured in the Far Term. A focus of future work is to continue to make improvements to the roadmap process through better prediction of noise sources and treatments, higher fidelity acoustic modeling of technologies, and the addition of new technologies where opportunities or need exists. An additional avenue of improvement is to make configuration changes in a multidisciplinary design process rather than an acoustic design process alone.

The primary conclusion of this work is that the TW301 does not provide an architecture that is well suited to meet the NASA noise goals. While it does appear able to maintain the historical margin relative to current regulations through 2035, it is unlikely to deliver a step change in aircraft noise.

Acknowledgments

The Aircraft Noise Reduction Subproject of the Advanced Air Transport Technology Project is acknowledged for funding of this work. The authors would like to thank John Rawls and Stuart Pope for their contributions to this paper and the PAA and Aircraft System Noise team. Jason June would like to thank Kyle Pascioni and Michael Jones for their technical review.

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