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Special Session – Towards A Silent Aircraft

Development of Approach Procedures for Silent Aircraft

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Aircraft technology and operational procedures need to be designed in parallel to meet the Silent Aircraft Initiative noise goal of being below ambient noise levels outside the perimeter of a typical urban airport. Technologies have been incorporated into a conceptual Silent Aircraft blended-wing-body type design allowing a slow and steep continuous descent approach trajectory with a displaced landing threshold. Through the use of advanced airframe design combined with deployable drooped leading edge, elevator deflection and thrust vectoring, a trimmed approach trajectory has been developed for the Silent Aircraft with a flight path angle of 3.9°, velocity of 60.8 m/s (118 kts) and threshold displacement of 1.2 km. In addition, the engines operate at idle thrust to lower noise and reduce the amount of drag that needs to be generated to trim the aircraft. This approach trajectory results in a peak noise level of 61 dBA outside the airport perimeter, a level comparable to background noise levels. This procedure would meet go-around maneuver requirements, but could affect the runway capacity at the airport unless such operations were segregated from conventional approach procedures.

I. Introduction

THE Silent Aircraft Initiative (SAI), a collaborative effort between the Massachusetts Institute of Technology and the University of Cambridge, has the goal of developing a conceptual aircraft design whose noise impact would be below ambient levels around a typical urban airport. To achieve this step change in noise reduction, noise has to become a primary variable in the aircraft design process.[1] The outcome of this research effort has been a Silent Aircraft eXperimental (SAX) conceptual design for an aircraft that could carry 215 passengers, with a range of 5,000 nm in a blended-wing-body type airframe[2] that utilizes a distributed, boundary layer ingesting propulsion system.[3,4] This paper presents the suite of candidate low noise technologies and operating concepts that are relevant during the approach phase of flight. Details of the takeoff operations[5] and economic factors[6] are also discussed in companion papers.

A. Nature of the Problem

During approach, the dominant airframe source contributions are from the undercarriage, the high-lift devices, the control surfaces, drag augmentation devices, and the scattering of boundary layer turbulence at the trailing edges; while the dominant engine noise typically originates from the fan and low pressure turbine. Major advances in noise reduction have been made over the last few decades through the wide-spread introduction of high bypass

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ratio turbofan engines, while future advances are targeting the treatment of individual noise sources to reduce the shedding of turbulence or to shield the ground from noise sources. Continuous mold-line technology, slat cove treatments, fan inlet scarfing and undercarriage fairing are ideas to further reduce aircraft noise during approach.[7-9] However, to achieve a radical reduction in approach noise levels from today's aircraft requires the reduction or elimination of all sources of noise, including the noise emitted by the scattering of turbulence from the trailing edge of the lifting surfaces. Treating all of the noise sources individually will not yield the SAI noise goal and therefore an integrated approach to the overall aircraft design and operations is required.

Sound pressure levels from airframe sources have an intensity proportional to $(\text{velocity})^n$, where n is 5 for trailing edge scattering (airfoil self-noise) and 6 for dipole type sources such as the undercarriage.[10] Therefore lower approach speeds and/or clean aerodynamic configurations can significantly reduce the noise of approaching aircraft. A low idle thrust setting reduces the loading on the fan blades and hence also reduces the magnitude of the resulting broadband and tonal noise significantly. The change in engine rotational speed may shift the blade passing frequencies into a range with a higher A-weighting, which acoustic treatment should be capable of addressing.

The sound pressure level from all noise sources is also logarithmically proportional to $1/(\text{distance})^2$. Steeper approach angles therefore reduce noise impacts by keeping aircraft at higher altitudes for a given distance from touchdown. In addition, displacing the landing point further down the runway effectively increases the altitude of the aircraft a given distance from the runway, thereby reducing noise at and outside the airport perimeter in the same fashion to steep approaches. Every 1 km of displacement provides approximately 170 ft of increased altitude at the airport perimeter for a conventional 3° approach.

One of the most promising operational techniques for approach noise abatement in the current air traffic control (ATC) system involves Continuous Descent Approach (CDA) procedures that eliminate level segments, keeping aircraft higher and at lower thrust levels for longer than conventional "step-down" approach techniques. This can reduce noise impacts by a noticeable amount in the initial approach phase prior to final approach.[11] However, today's uses of CDAs generally terminate in a conventional 3° final approach to touchdown, providing no noise benefits immediately surrounding the airport where the noise levels are highest. This paper proposes a modification to the CDA procedure which takes advantage of its benefits during the initial approach phase while also significantly lowering noise near the airport perimeter through a combination of elements detailed below.

B. Technical Solution

The final Silent Aircraft conceptual design, SAX-40 is shown in Figure 1 and achieves the SAI noise goal through the implementation of an approach procedure that incorporates a CDA with slow approach velocity, steep approach angle, displaced landing threshold, low approach thrust and quiet aerodynamic configuration enabled by advanced technologies. This reduces noise via the four key variables:

- <u>Approach Velocity</u>: The Silent Aircraft design utilizes an all-lifting body with large surface area, which when combined with aerodynamic shaping of the leading edge of the centerbody leads to an estimated approach speed of 60.8 m/s (118 kts), a 28% reduction as compared to current aircraft of similar size.
- <u>Altitude</u>: The Silent Aircraft utilizes a steep approach path of 3.9° and a runway displacement of 1.2 km to increase the distance between the aircraft and the ground during the approach phase of flight. These increase that altitude by 320 ft at the airport perimeter compared to a conventional 3° non-displaced approach.
- <u>Engine Operation / Design:</u> The engine operates at 45% speed during approach (45% N1), all the way to touching down, to lower noise and facilitate drag trim. This differs from ideal CDAs currently in use that utilize flight idle speed (approximately 30-40% N1) prior to ILS (instrument landing system) intercept, but then have engines spool up to higher speeds (approximately 60-70% N1) afterward. Additionally, the engine low pressure turbine was designed for reduced noise.[4]
- <u>Approach Configuration</u>: With the use of an all-lifting-body, flaps are unnecessary on the design thus eliminating a significant noise source. Airframe components are designed to reduce the shedding of turbulence. Examples include a deployable drooped leading edge for lift augmentation,[12] faired landing gear,[13] trailing edge brushes,[14] and continuous mold-line technology[7] on the elevons. Additionally, the all-lifting-body airframe provides large surface area for shielding[15] of forward radiating engine noise and allows for extensive acoustic liners[16,17] to mitigate aft radiating engine noise. The distributed propulsion system allows for a smaller fan diameter. This in turn allows the liners to remove more acoustic energy as the length-to-diameter ratio of the ducting increases drastically.

Figure 1: *S*ilent *A*ircraft e*X*perimental design SAX-40.

The combined impact of these changes results in a maximum noise of 61 dBA at the airport perimeter. The ground noise footprint as the aircraft passes the airport perimeter is shown in Figure 3 along with the individual components that make up the footprint. The dashed line in the ground noise footprint shows the airport perimeter while the solid black line represents the aircraft flight path which is then broken out within the line plot. The dominant noise sources are fan rearward and faired undercarriage. The Effective Perceived Noise Level (EPNL) was estimated as 71.9 EPNdB; it should be noted that this value does not include tone corrections. Figure 3 presents the SAX noise level along a conventional 3.0° glide slope in comparison to US certified noise levels[18] for the existing fleet and it quantifies the large change in noise emission that is expected from the SAX design.

C. Scope of the Paper

The objective of the remainder of this paper is to present the details behind the slow, steep and displaced threshold approach procedure and give insight into how a step change in approach noise was achieved relative to current aircraft. The sections are roughly broken into the following topics:

- Analysis techniques to estimate the noise from the slow, steep, and displaced threshold SAX-40 approach.
- Airframe and engine technologies that not only enable a slow, steep, and displaced threshold approach, but that also pass the defined operational limitations.

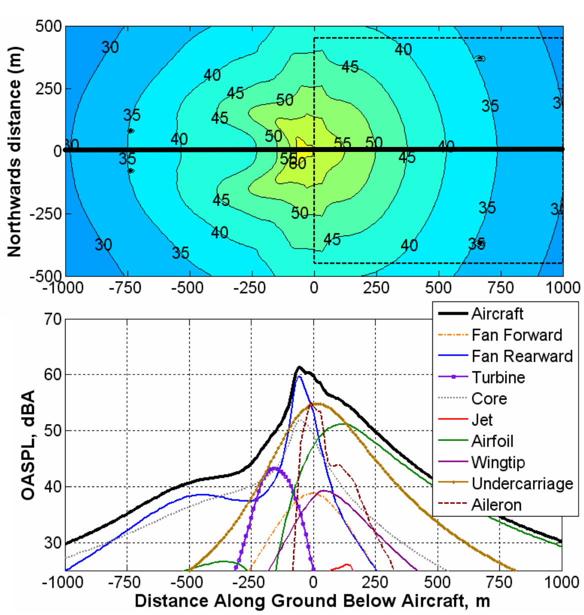

Figure 3: Estimated SAX-40 approach noise footprint [top] and components [bottom] at airport perimeter.

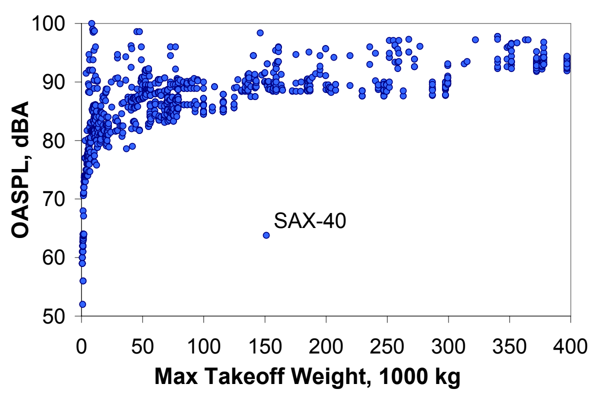

Figure 3: Over All Sound Pressure Level at 2 km from touchdown for all Stage-3 certified aircraft[18] compared to estimate for SAX40 on a 3.0° approach.

- Operational feasibility and limitations on a slow, steep, and displaced threshold approach.

II. Noise Estimation

The ground noise estimates shown in Figure 3 were calculated using a combination of empirical relationships and experimental measurements based upon a hypothetical airport definition. This airport is shown schematically in Figure 4 and was defined after assessment of numerous international airports, but is ultimately similar to London Heathrow. The distance from the airport perimeter to the start of the runway was set at 1 km while the runway length of 3 km is typical of large airports. The required maximum 'silent' operating temperature was set to ISA+12°K to capture 99% of operations within the London area.[19] The increased air temperature results in decreased air density and faster, noisier approaches than cooler conditions.

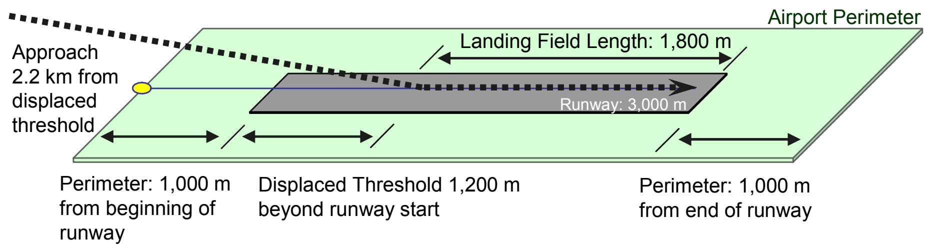

Figure 4: Hypothetical airport dimensions used for the SAX-40 approach noise estimate.

The engine noise sources and liner attenuation of forward propagating noise have been estimated using industry standard prediction tools. These consider all significant engine noise sources relating to the jet, fan, turbine, compressor and combustor. The modeling has been described at length in a companion paper on the takeoff procedure.[5] The considerable benefits gained by shielding of forward propagating noise by the SAX airframe have been estimated by Agarwal and Dowling[15] using ray theory methods. After obtaining a source distribution, they assumed that the sound in the shadow region can only have reached the observer through either sharp edge diffraction or via creeping rays. The superposition of the resulting sound from the two mechanisms provides the noise beneath the aircraft. For the long mixed exhaust, rearward propagating engine noise is modeled by solving appropriate eigenvalue problems for uniform axial inviscid flow in annular and cylindrical lined ducts.[16,17] From the resulting modal amplitudes at the nozzle termination, the final radiated sound pressure level is estimated using the Wiener-Hopf solutions from an unflanged duct.[20,21]

The modeled airframe noise sources consist of the undercarriage, ailerons, wing tips, deployable drooped leading edge and boundary layer scattering from the airfoil trailing edge. The undercarriage noise prediction is based upon the experiments of Quayle et al.[13] The aileron noise was based upon Guo et al.[22] and Sen et al.,[23] relying upon empirically based correlations to Mach number, aileron span, aileron chord, lift coefficient and deflection. A deflection of 1° was incorporated for the estimate in Figure 3; a 5° deflection causes the aileron noise to increase by 1.3 dBA. The noise generated by the wingtips was estimated via the semi-empirical tip vortex formation noise component of Brooks et al.[24] This noise source is modeled as scattering of the wingtip vortex turbulence as it passes over the trailing-edge of the wing. Based upon the experiments of Andreou et al.,[12] the noise generated by the deployable drooped leading edge was assumed to be comparable to that from the scattering of turbulence from the airfoil trailing edge and was ignored.

The noise emission from the scattering of turbulence from the airfoil trailing edge was estimated using empirical relationships[10,25] with a correction for trailing edge sweep.[26] A glider amplitude noise estimate was used to model the clean all-lifting body for the SAX design as it is expected to have airfoil noise characteristics similar to a high performance sailplane. The trailing edge aft of the engines was not modeled as a trailing edge noise source because this region would be filled by the jet exhaust. Airfoil self-noise mitigation through

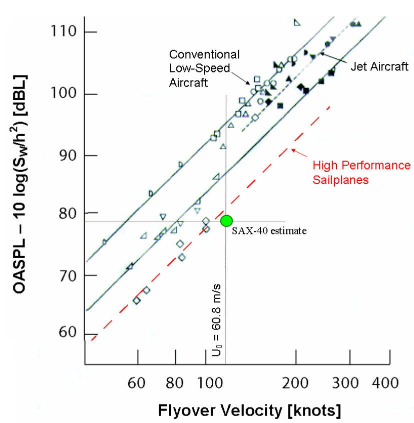

Figure 5: Airfoil self-noise normalized by wing area and height as a function of velocity. Data from Fink.[24]

the use of trailing edge brushes outboard of 12.8 m was estimated based upon the measurements of Herr and Dobrzyinski[14] with a brush length that is 3.8% of the local chord. The airfoil self-noise estimate, without trailing edge brushes, is compared to the measurements presented by Fink[25] in Figure 5 and shows the noise emission is indeed similar to high performance gliders.

Acoustic energy was propagated from the source to the ground using the techniques described by Evans[27] which assume spherical spreading, atmospheric attenuation within a still, uniform medium and attenuation / amplification of acoustic energy due to incidence onto a grassy surface. A +3dB correction was made for ground reflection. Effective perceived noise levels (EPNdB) were computed according to the FAA procedures documented in Part 36 with the exception of neglecting tone corrections, [28] which were not computed for airframe noise sources. The component and total perceived noise levels that were used to estimate EPNL are shown in Figure 6.

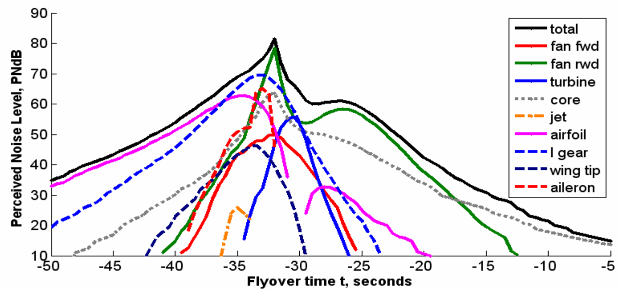

Figure 6: SAX-40 perceived noise level used in calculation of EPNdB. Time is relative to aircraft touching down 2 km from observer.

III. Enabling Technologies

A. Aircraft Trim

One of the most important aspects to determine feasible approach trajectories is the maintenance of aircraft trim. Aircraft trim during approach was determined via balance of the aerodynamic forces during steady approach conditions. Figure 7 depicts the forces that were modeled for the force balance. The aerodynamic lift, L, balances components of the weight, mg, and thrust vectoring, T_v, while the aerodynamic drag, D_{aero}, combined with the engine ram drag, D_R, and landing gear drag, D_{gear}, balance components of the thrust and weight. A two-dimensional vortex lattice[29] solution was used to estimate lift and induced drag. The parasitic airframe drag was estimated on the outer wings using a two-dimensional viscous airfoil design and analysis tool[30] while that on the centerbody was estimated using empirical relations.[31] The drag from the faired landing gear was estimated as 0.0040 based upon wind tunnel measurements.[13] The moment due to thrust vectoring combined with elevator deflection balances the aerodynamic moment, M_{aero}, the moment caused by the landing gear, and the aerodynamic moment caused by embedding the engines, M_{inlet}. The aerodynamic pitching moment and elevator deflection for pitch trim were estimated from a combination of vortex lattice solution while the nose down pitching moment caused by the acceleration of air into the engine inlets was modeled based upon a low speed three-dimensional vortex panel calculation.

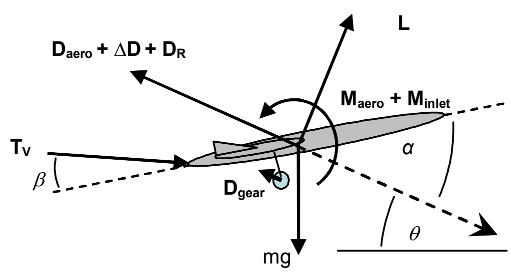

Figure 7: Aircraft force balance during a steady approach.

The SAX-40 design is trimmed using a combination of thrust vectoring and elevator deflection. In addition to trimming the pitching moment, the combination is used to increase the induced drag being generated by the airframe which enables a steeper approach path. Table 1 presents the conditions necessary to trim SAX-40. Of note, SAX-40 could be flown with the existing fleet on a 3° flight path using 17.4° of downward thrust vectoring with an increase in noise of 1.5 dBA over the 3.9° flight path configuration. Directing thrust downward (negative angles) requires increasing elevator deflections to pitch trim the aircraft and this requires a larger angle of attack because (1) the aft section of the outer wings are unloaded and (2) the thrust is acting opposite lift. The increased lift is accompanied by an increase in induced drag, and a steeper approach path is necessary for trim thus increasing the distance between the aircraft and the ground and reducing noise impact. A gain in induced drag of 0.0049 results from increasing the thrust vectoring angle from zero to 30°, this is equivalent to a drag device with a frontal area of 4.1 m^2 generating a drag coefficient of 1.0. Minimum noise occurs with maximum downward thrust vectoring as this maximizes both the induced drag and the flight path angle; for this reason, 30° of downward thrust vectoring was chosen for approach trim.

Table 1: Control requirements, induced drag & noise generation from a trimmed SAX for flight path angles between 2.5 and 3.9°. Analysis assumed an approach speed of 60.8 m/s and threshold displacement of 1.2 km.

Flight Path Angle, °	2.5	3.0	3.5	3.9
Angle of Attack, °	14.5	15.0	15.4	15.6
Thrust Vectoring Angle, °	8.3 down	17.4 down	24.8 down	30.0 down
Elevon Deflection, °	12.3 up	15.0 up	17.1 up	18.5 up
Induced Drag Coefficient	0.0328	0.0342	0.0356	0.0365
OASPL, dBA	63.2	62.7	61.9	61.4
Fan Rearward Noise, dBA	51.8	53.1	53. 4	54.2
Airframe Noise, dBA	62.0	61.5	60.6	59.8

B. Lift Augmentation

The stall speed characteristics of the SAX-40 aircraft are compared with and without a deployable drooped leading edge in Table 2. The trimmed stall speed was estimated using an iterative process that combined a two-dimensional vortex lattice and two-dimensional airfoil design codes whereby the elevator deflection and airfoil loading were analyzed. In line with FAR 25.125,[32] the approach speed used for noise estimation was chosen as 1.23 times the stall speed. The self-noise estimate uses a distance of 2.2 km from touch down to set the height and it does not include the impact of brushes. With a droop of 27°, the maximum sectional outer wing airfoil lift coefficient was estimated as being above 2.2 from the outer wing airfoil at zero elevator deflection, an increase of 0.3 over the baseline airfoil. The deployed drooped leading edge reduces the stall speed by 3.5 m/s, the approach speed by 4.3 m/s, and the airfoil self-noise decreases by 1.7 dBA.

Table 2: SAX-40 performance comparison with and without deployment of a 27° drooped leading edge outboard of 9.1 m.

	None	Drooped Leading Edge
Stall Speed, m/s	52.9	49.4
Approach Speed, m/s	65.3	60.8
Angle of Attack, °	18.7	21.9
Elevator Deflection for trim, °	-12.4	-16.0
Airfoil Self-Noise w/ L.E. Device, dBA	59.5	57.8

If the SAX-40 drooped leading edges were replaced by conventional slats, the slat noise would be 65.2 dBA at an approach speed of 60.8 m/s; this estimate was computed using empirical relationships.[10] To get conventional slat noise down to 57.8 dBA, which is the airfoil self-noise level at 60.8 m/s, the aircraft would need an approach speed of 46.1 m/s. This low approach speed requires an aircraft stall speed of 37.5 m/s and an aircraft lift coefficient of 1.71; these are unrealistic values as a vortex lattice solution predicts an angle of attack of over 50° being necessary to generate this coefficient of lift. Based on the decreased noise level that results from their use, a deployable drooped leading edge was chosen for the SAX-40 design.

C. Engine Idle Speed

The Granta-3401 engines on SAX-40 have been designed to operate at low idle thrust. This is possible because of the variable area nozzle that enables an ultra low engine rotational speed during approach while meeting the go-around maneuver requirement. During approach, the engine speed operates at 45% of the design speed at top-of-climb, N1.

As discussed in aircraft trim, the aerodynamic drag must balance a component of the engine thrust. Therefore, excessive engine thrust must be balanced by the generation of aerodynamic drag, which inherently creates noise. The Granta-3401 engines generate 79 kN of thrust while operating at 60% speed, but only 33 kN while operating at

45% speed. Hence, operating at 60% engine speed requires an increase in aerodynamic drag coefficient of 0.0253 as compared to operation at 45% speed. In addition to the reduction in approach airframe drag requirement, the reduced operating speed gives rise to reduced fan rearward noise emission.

The transient response of the engine was modeled at this low rotational speed to ensure safe operation for a go-around procedure. The variable area nozzle closes from its normal value during approach operations to that of top-of-climb to increase the low pressure spool speed to give adequate thrust for go-around. A handling bleed of 24.6% of the inlet mass flow for the intermediate pressure compressor and 8.5% for the high pressure compressor is used to maintain a sufficient surge margin on approach and during the transient operation. The transient analysis gives a spool-up time of 5 seconds to go from the thrust required nominally during to 100 kN, which ensures that the go-around procedure can be performed quickly and safely (discussed in a subsequent section).

D. Slow and Steep Approach Path Trade Space

The aerodynamic requirements to fly a range of approach velocities and flight path angles are presented in plots I-III of Figure 8. As discussed above, thrust vectoring was set to 30° downward to maximize flight path angle via induced drag generation. Some of the approach trajectories would not be available because (1) go-around maneuver requirements (discussed later) and (2) approach speeds below 60.8 m/s would violate the FAR 25.125 requirement that approach speed exceed 1.23 times the stall speed. To trim the pitching moments at lower speeds, large upward elevator deflections are required. Because elevator deflection unloads the aft airfoil sections, large angles of attack are required to generate the requisite lift. Increasing flight path angle requires significant drag generation. For example, the drag requirements to fly a 5° and 6° angle of attack at 60.8 m/s are 0.0127 and 0.0241, respectively, based on the SAX-40 planform area. The SAX-40 would require 10.6 m^2 and 20.1 m^2 of frontal area from a drag device with a drag coefficient of 1.0. This drag could potentially be quietly generated by perforated drag plates Sakaliyski et al.[33] or via a novel, quiet engine airbrake concept that uses steady swirling flow to generate pressure drag Shah et al.[34]

As shown in plot IV of Figure 8, approach trajectory also impacts landing field length and feasible threshold displacement on the 3 km runway (analysis presented in a subsequent section). Threshold displacements that are less than zero require a runway that is longer than 3 km and are not possible at the hypothetical airport that was depicted in Figure 4.

The aircraft noise levels resulting from varied approach trajectories are presented in plot V; these noise data include the impact of threshold displacement on aircraft altitude that was depicted in plot IV of Figure 8. The airframe noise was scaled on velocity assuming drag could be trimmed at a noise level below that of the aircraft. Because of this, higher velocities are airframe noise dominated while lower velocities are fan rearward dominated. The fan rearward noise decreases with flight path angle due to increasing distance and it decreases with velocity because of decreases in the accompanying angle of attack. As the angle of attack reduces, fan rearward noise is directed upward, away from the ground. Of note, Plot V includes approach trajectories that would not be feasible due to requirements on stall speed (must exceed 60.8 m/s, 1.23 x stall speed), runway length (positive values from plot IV), and go-around maneuver (discussed in the next section).

The approach trajectory was chosen with an approach speed of 60.8 m/s and flight path angle of 3.9° to achieve a maximum noise level of 61 dBA during the approach phase of operation. This trajectory required the engines to operate at 45% speed while the SAX-40 aircraft requires 15.6° angle of attack, 27° of deployable drooped leading edge, 30° of downward thrust vectoring, and 18.5° of upward elevon deflection.

IV. Operational Feasibility and Analysis

A. Certification / Regulation Considerations

1. Approach Speed

Reducing approach speed leads to a significant decrease in airframe noise, but there is a limit on how low the approach speed can go. Regulations (e.g. JAR 25.125) require the approach speed exceed 1.3 times (or 1.23 times in the equivalent FAR) the stall speed in the approach configuration. Lower approach speeds therefore require low stall speed aerodynamic configurations, which requires the deployment of high-lift devices which are themselves significant noise sources. This is an example of a trade-off required in the development of low noise approach procedures that hence drive the need for low noise high lift devices. There are also ATC implications of approach speeds significantly different than the current operating range (typically 120-160 knots for current medium-sized commercial aircraft).

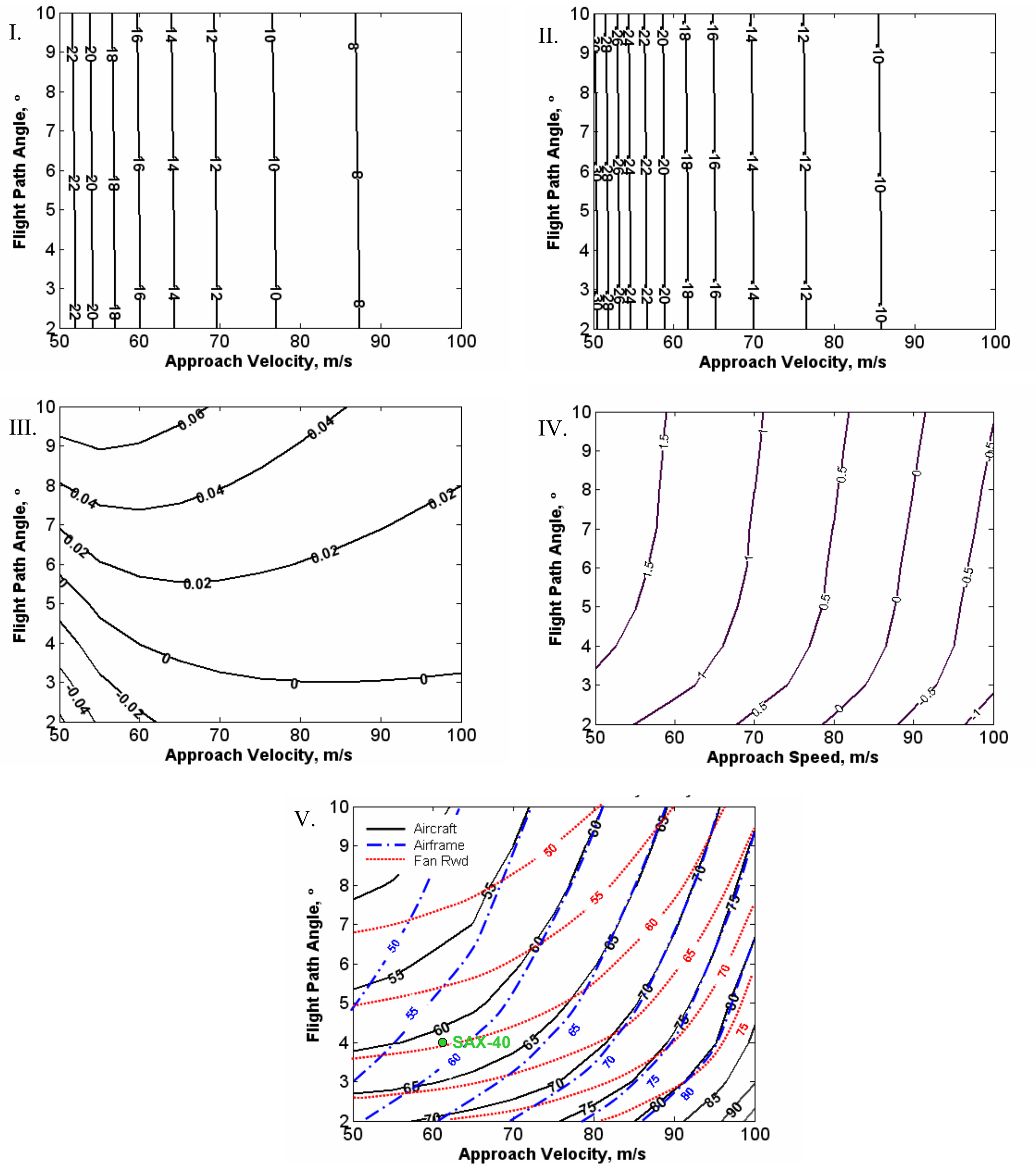

Figure 8: Impact of approach trajectory on SAX-40 (I) angle of attack, (II) elevator deflection, (III) change in drag to trim the aircraft, (IV) feasible landing threshold displacement (in km) on the 3 km design runway, and (V) aircraft noise at the airport perimeter with components from airframe and fan rearward.

2. Flight Path Angle

The benefits of steep approaches are well-known: flight trials have been conducted since the 1970s,[35] while more recent analytical studies have assessed their potential benefits.[36,37] In practice, steep approaches are relatively difficult to achieve with conventional aircraft types. In order to undertake steep approaches with the A318, a steep approach architecture for the Flight Control System and a modified aerodynamic configuration for this mode involving flaps and slats fully extended, landing gear down and speedbrake panels 3 and 4 extended to 30°, had to be developed.[38]

Most current conventional approaches are conducted at 3-3.5°. However a few airports do require significantly steeper approaches and this limits the aircraft that can use them. For example, a 5.5° approach angle is required at London City Airport due to noise and high-rise building constraints, while Lugano in Switzerland has a 6.65° approach due to terrain. UK Civil Aviation Authority (CAA) guidance on steep approaches[39] indicates that approach angles up to 3.5° are considered "routine" for any certificated aircraft, angles 3.5-4.5° are "unlikely to produce significant problems in normal operations, but operators which encounter such procedures should consult with the aeroplane manufacturer to satisfy themselves that the performance and handling characteristics are satisfactory at this angle", while approach angles above 4.5° need specific operational and airworthiness approval. Therefore, the Silent Aircraft approach angle of 3.9° appears reasonable from a regulatory perspective.

3. Displaced Threshold

The standard landing threshold is near the end of the runway to maximize the landing distance available, but this does not have to be the case as long as sufficient runway length for landing can be assured for a given aircraft type. Frankfurt Airport in Germany has been conducting displaced threshold approaches with medium-sized aircraft since 1999 as part of its High Approach Landing System/Dual Threshold Operation (HAL/DTOP) program.[40] They have tested a system that utilizes a displaced threshold of 1500 m on runway 25L (with displaced approaches being designated to runway 26L) to reduce the likelihood of wake vortex interaction between approaches to the airport's parallel runways. Although not explicitly for noise reduction, the extensive use of this configuration at Frankfurt has set the operational precedent for displaced threshold approaches which are similar to those being proposed for the Silent Aircraft.

B. Landing Field Length

Displacing the landing threshold obviously decreases the runway length available for landing and this must be accounted for when determining which aircraft types can use the procedure and how much displacement is feasible on a runway of a given length. It also affects the runway exit and taxi times from the runway. The elements that need to be considered in a landing analysis are given in the top of Figure 9. Regulations (JAR/FAR 25.125) start the landing analysis in a stabilized approach at 50 ft above ground level and increase the total landing distance by appropriate safety factors to account for pilot variability and runway condition. Using a standard empirical approach to calculating each of the elements making up the complete landing run[41] and open-literature-published aircraft data, a comparison of the landing field length for different aircraft types is presented in the bottom of Figure 9. The results illustrate that as conventional aircraft sizes increase, the landing field length also typically increases. However, displacements of approximately 0.5 to 1 km are feasible with all of these aircraft types with a 3 km long runway. But all of these feasible displacements would only be useful if exits were available at appropriate places along the runway. There are also significant infrastructure implications to displacing thresholds, for example with regards runway lighting, markings and guidance systems.

Results for the SAX-40 design, one with a conventional 3° approach and one with the steeper 3.9° approach angle are also included. These designs have much lower wing loading and slower approach speeds which results in shorter landing field length compared to conventional aircraft of a

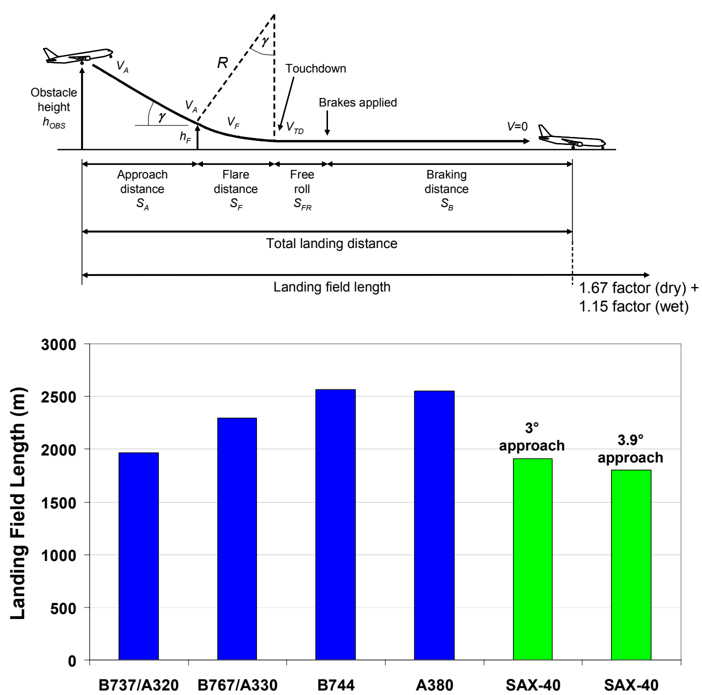

Figure 9: Landing field length analysis.

similar size. A landing displacement of 1.2 km is possible with the SAX-40 on a 3 km runway. A 1.2 km landing displacement combined with the 3.9° approach angle increases the aircraft altitude at the airport perimeter to 542 ft from an altitude of 274 ft for a non-displaced 3.9° approach and 222 ft for a non-displaced approach using a conventional 3° flight path angle. Respective noise reductions of 5.9 and 7.8 dBA are expected for the steep displaced approach in relation to the steep non-displaced, and conventional, non-displaced approach paths.

C. Go-Around Considerations

An analysis was undertaken to determine the operational constraints on flight path angle and final approach speed to conduct a safe (i.e. no ground contact) go-around procedure executed from a given decision height. A simplified model of this go-around scenario is presented in Figure 10. The key variables involved in the model, in addition to flight path angle, γ and approach speed, $V_{approach}$ are: decision height, DH (height at which the decision is made to initiate a go-around); pilot/aircraft delay, T_{delay} (delay time between decision to initiate go-around and start of change of the aircraft's flight path due to lags introduced by the pilot, engine spool-up and aircraft inertia); and the load factor limit, n_{limit} (limit on aggressiveness of the pull-up).

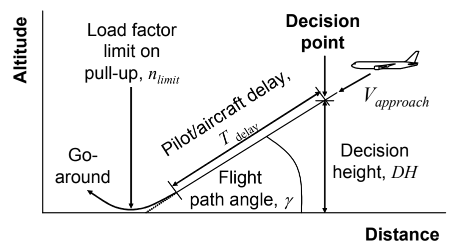

Figure 10: Go around analysis.

Assuming a point mass and circular arc simplification of the pull-up trajectory, the requirement for the aircraft to not contact the ground during the go-around procedure can be expressed as:

$$DH > V_{approach} T_{delay} \sin\gamma + \frac{V^2_{approach}}{(n_{limit} - 1)g}(1 - \cos\gamma) \qquad \text{Eqn. 1}$$

In order to use this to determine the maximum safe flight path angle as a function of approach speed, typical values of DH, T_{delay} and n_{limit} were determined. The most common minimum decision height in use in current operations is 100 ft; experimental studies of pilot/aircraft delay times during final approach operations found typical values of 3-5 secs.[42] As discussed in the engine idle speed analysis, the engines for the Silent Arcraft would require a 5 second spool-up time. Current operating guidelines for airline pilots suggest load factor limits of 1.3g are appropriate for passenger comfort requirements. However, because there is no direct display of g-level available to the pilot, this is only a guideline and therefore load factor limits of 1.3±0.1g were considered an appropriate range in this analysis. Given these typical values for each of the model parameters, a plot of the maximum safe flight path angle as a function of typical aircraft final approach speed ranges is presented in Figure 11. The current operating regime for conventional aircraft of 3-3.5°/120-160 kts is also presented for comparison. It is apparent that the delay time parameter dominates the location of the curves. By contrast, the load factor limit impact is relatively small. Taking a 5 sec delay time, the maximum flight path angle is limited to approximately 3.5-5° for 120-160 kts final approach speeds typical of conventional aircraft (i.e. not a large change from today's regime), while a 3 sec delay time increases the limit to approximately 5-6.5°. The feasible regions with larger flight path angles are associated with lower approach speeds, making it easier to support slower/steeper operating procedures. The SAX-40 approach trajectory parameters fall well within this region, as shown.

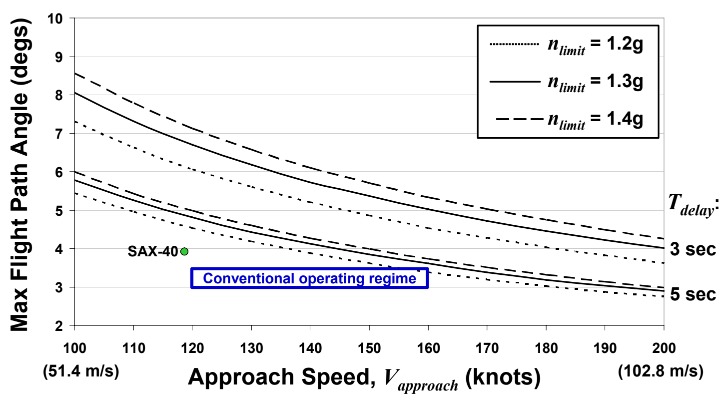

Figure 11: Results from SAX-40 go-around analysis with range of current operations.

Using the dynamical model and controller presented by Thomas and Dowling,[43] the actual dynamical response of SAX 40 to both a go-around input and a strong trailing gust were analyzed. For go-around, the controller was given a sudden input command to transition between a 4º descent and a 4º climb. The aircraft performed the transition after a loss of height of less than 20m, while remaining inside the safe flight envelope. A strong trailing gust was also simulated. At the nominal approach conditions, the aircraft recovered the glide slope after a drop of 15m, while remaining inside the safe flight envelope. If a stronger gust of 15m/s was simulated, the aircraft still managed to regain the glide slope with a small loss of height; however, the angle of attack exceeded the stall margin, due to the low approach velocity. Therefore, in exceptionally gusty conditions, a faster approach may be necessary to ensure safe aircraft operation.

D. Runway Capacity Impact

Changing the approach profile relative to current conventional aircraft has operational implications. One of the main impacts would be on the maintenance of separation between Silent Aircraft on slow/steep/displaced approaches and conventional approaches to the same runway. ATC wake vortex separation criteria require certain minimum distances to be maintained between consecutive aircraft throughout approach operations. When one aircraft approaches significantly slower than the aircraft ahead or behind, it complicates the air traffic control process of maintaining the required separation minima throughout the approach. Under these conditions today, controllers often employ additional separation buffers (above and beyond the minimum requirement) to account for the projection uncertainty resulting from the different aircraft approach speeds, impacting runway capacity. Similar uncertainty could be introduced with steep approach angles or displaced thresholds, as are proposed for the Silent Aircraft.

A simple model for the saturation capacity, C, of a runway can be represented as:[44]

$$C = \frac{1}{E(t)} = \frac{1}{\sum_i \sum_j p_{ij} . t_{ij}} = \frac{1}{\sum_i \sum_j p_{ij} . [T_{ij} + b_{ij}]} \qquad \text{Eqn. 2}$$

where $E(t)$ is the expected time between aircraft using the runway; p_{ij} is the probability of occurrence of aircraft type i followed by type j; t_{ij} is the average time interval between successive movements of type i and j such that no ATC separation requirements are violated. t_{ij} can be expressed as being the sum of T_{ij} and b_{ij}, where T_{ij} is the theoretical minimum time separation required between aircraft type i and j and b_{ij} is the buffer added by a controller to make up for imperfections in the ATC system and to account for their own uncertainty in projecting the positions of the aircraft of the given types.[45] The theoretical minimum time separation required between aircraft type i and j, T_{ij}, is itself a function of several key variables. For a runway that just handles arrivals:

In an opening case (i.e. $V_i > V_j$): $T_{ij} = \max\left(\frac{n + s_{ij}}{V_j} - \frac{n}{V_i}, o_i\right)$; In a closing case (i.e. $V_i < V_j$): $T_{ij} = \max\left(\frac{s_{ij}}{V_j}, o_i\right)$ Eqn. 3

where n is the length of the final approach path; s_{ij} is the wake vortex separation requirement between aircraft types i and j, V_i is the approach velocity of aircraft type i and o_i is the runway occupancy time of aircraft type i. The separation requirements are imposed longitudinally between aircraft approaching a runway (see Figure 12) to reduce the threat of encounters with wake vortices generated by preceding aircraft, which can cause significant attitude deviations if the following aircraft is too close. In the opening case, aircraft type j is slower and minimum separation requirements are therefore required at the entry to the final approach, while in the closing case, aircraft type i is slower and minimum separation is required at the runway threshold.

This runway capacity model was used to assess the impacts on runway capacity of different combinations of ATC-imposed buffer; wake vortex separation minima; approach velocity and % silent approaches in the traffic mix (the balance being heavy & large conventional aircraft). In the absence of specific changes to the wake vortex separation minima required for the SAX-40 design, it is possible to utilize the ATC-imposed buffer (b_{ij} in Eqn. 2) as a surrogate for any increased separation requirements or to account for the increased controller uncertainty introduced by the use of silent approaches with slower approach velocity, steeper angles and displaced threshold.

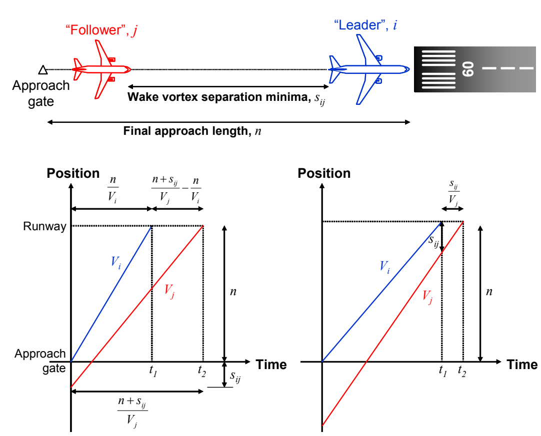

Figure 12: Graphical representation of opening (left) and closing (right) approach cases. Adapted from [44].

Using the analysis parameters shown in Table 3, the capacity implications of differing ATC-imposed buffer, traffic mix and speed of silent approaches relative to the capacity with purely conventional approaches are given in Figure 13. The left results show the runway capacity (relative to all conventionals) as a function of buffer and proportion of silent approaches of velocity 120 kts. The balance of the traffic is conventional heavy aircraft with approach velocities of 140 kts. The presence of differing proportions of opening and closing aircraft pairs make the capacity non-linear with % silent approaches. Relative capacity decreases linearly with buffer, with a minimum of approximately 70% capacity with a 20 sec buffer and 70% steep approach traffic mix. The right hand side of Figure 13 presents the capacity impacts as functions of silent approach velocity and buffer for a fixed traffic mix of equal proportion of heavy conventional aircraft, large conventional aircraft and heavy silent approaches relative to the capacity with 50% heavy and 50% large conventional approaches. It is seen that the capacity drops significantly as the silent approach speed is reduced below that of heavy and large conventional aircraft due to the presence of greater opening case separations and the overall longer times involved with a given wake vortex separation distance with lower approach speeds. Less significant capacity reductions are seen with silent approach speeds higher than the conventional aircraft because the given distance separation requirements take less time.

Table 3: Capacity analysis parameters.

Weight category	Approach speed	Runway occupancy time	% Traffic mix
Heavy conventional* (Hc)	140 kts	60 secs	%Hc
Large conventional* (Lc)	120 kts	55 secs	%Lc
Heavy silent (Hs)	Vs	50 secs	%Hs
Final approach length	10 nm		
Wake vortex separation minima	As in FAA Air Traffic Control Handbook[46]: 5 nm (Large behind Heavy); 4 nm (Heavy behind Heavy); 3 nm (Heavy or Large behind Large)		
ATC-induced buffer	Variable, with *b* secs added behind all approaches		

*Conventional aircraft data based on open literature sources

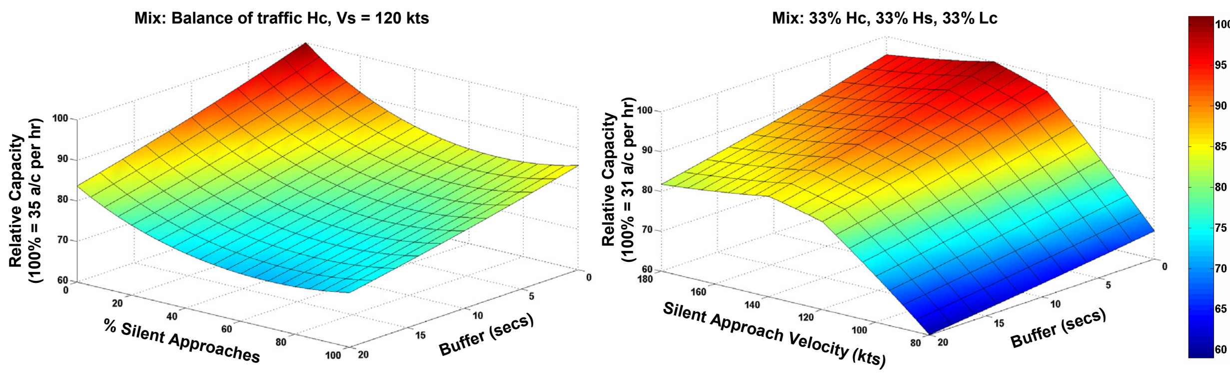

Figure 13: Capacity analysis of ATC-imposed buffer, proportion & velocity of silent approaches.

Overall these results illustrate that any new procedures that lead to increased ATC buffers can reduce runway capacity if combined with existing procedures. The loss of capacity due to an approach speed of 118 knots, the approach speed of the Silent Aircraft, could be between 5 and 20% depending on the traffic mix and buffer size. One way to minimize (or remove) these effects are to segregate operations, e.g. by having silent approaches conducted to specific runways or at specific times so they do not interact negatively with conventional approaches.

V. Conclusions and Implications for Existing Aircraft Designs

The Silent Aircraft Initiative has developed a conceptual design for an ultra-low noise (61 dBA outside the airport perimeter during approach) commercial aircraft that utilizes a variety of technical and operational innovations. The SAX-40 aircraft is capable of approaches at lower velocity, steeper approach angles and cleaner aerodynamic configuration than conventional aircraft. This is achieved through a combination of advanced blended-wing-body airframe design, elimination of flaps, a deployable drooped leading edge, undercarriage fairing and trailing edge brushes. Advanced engine design includes a variety of low noise technologies including ultra-high-bypass ratio distributed design, low noise low pressure turbine design and acoustic shielding. Operationally, the benefits of Continuous Descent Approach procedures (that are being utilized for noise abatement by conventional aircraft today) would be enhanced through the incorporation of steeper approach angles (3.9° versus a conventional approach of 3°), displaced threshold (1.2 km), and low engine thrust (45% speed all the way to touching down). The operational consequences of these modified procedures do need to be carefully considered, as discussed in the paper.

The noise benefits of these Silent Aircraft technologies and operating techniques could theoretically be used to obtain noise reductions in the shorter term with existing aircraft. For example, the quiet high lift and drag generation devices being developed for the Silent Aircraft may be suitable for retrofit to existing conventional aircraft designs. In addition, slow / steep / displaced approach profiles may be possible with conventional aircraft with modified procedures, technology or regulation.

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