Challenges and Opportunities for Noise Reduction Through Advanced Aircraft Propulsion Airframe Integration and Configurations

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Aircraft noise has been a public concern since the beginning of commercial jet powered aviation. Historical progress in noise reduction has been significant and largely made possible through land use planning, noise certification, and investment into low noise technology development. More recent progress however shows increasingly diminishing returns and suggests that new avenues may need to be discovered to pursue the aggressive noise reduction goals of the present and the future. This paper focuses on the research efforts of NASA in Propulsion Airframe Aeroacoustics (PAA) through advanced engine installations and configurations, which is offered as an avenue that has potential to provide significant noise reduction. PAA is further defined and the classification tree is presented as a means of organizing PAA effects. Several aircraft configurations and engine installations, both conventional and advanced, that are designed to take advantage of airframe shielding of engine noise are presented and discussed from both a PAA and a general design perspective. Other, non-shielding related PAA opportunities are also presented. Challenges to the eventual introduction of advanced aircraft configurations are discussed.

I. Introduction and Background

From the beginning of commercial jet powered aviation, the impact of aviation generated noise on the surrounding communities and the traveling public has been a significant issue. The measures that have been implemented to mitigate the noise problem have included land use planning, aircraft noise certification regulations, and airport noise restrictions. The latter two measures in particular have contributed to motivating the research and development of noise reduction technology. Covering a period of several decades from the introduction of the first jet powered aircraft, Fig. 1 shows the progress in net noise reduction from a variety of aircraft models and engines that have been certified. Using the Effective Perceived Noise Level (EPNL) at the sideline certification point (normalized to 100,000 lb of thrust) as the metric, the overall reduction has been about 20 dB. The majority of the reduction which occurred in the first three decades was due primarily to the introduction of high bypass ratio turbofan engines. The progress since about 1980 however has not been as dramatic and a much slower rate of noise reduction is observed. Even though production aircraft meet certification requirements, continued growth in air traffic and the limited introduction of new airports results in strong demand for the continued implementation of noise reduction technology. Another obvious implication from Fig. 1 is that the difficulty and cost of introducing new technology that significantly impacts noise reduction is increasing as the bulk of the noise reduction from higher bypass ratio engines has been achieved. This implication leads to the question of what are the opportunities and challenges to enable the next substantial amount of noise reduction similar to that achieved by the high bypass ratio engine.

The aircraft configurations that are represented in Fig. 1 are, with the exception of the DeHavilland Comet, of the three primary types that dominate commercial aviation. The first is the Engine-Under-Wing configuration which mounts its engines underneath the wings on pylons and the second is the Aft Fuselage configuration which mounts its engines on pylons attached to the fuselage toward the rear of the aircraft. The third and less common configuration is the tri-jet distinguished by an engine on top of the fuselage either below or through the vertical tail in addition to a pair mounted under the wings or on the aft fuselage. These three configurations were not introduced

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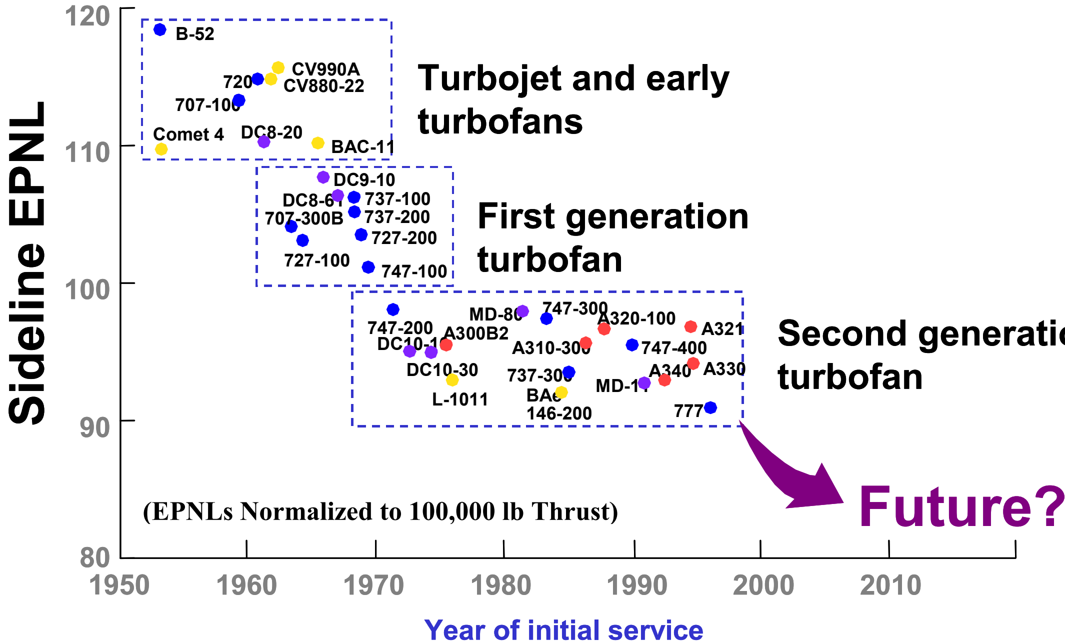

Figure 1. Historical Progress in Aircraft Noise Reduction (figure courtesy of The Boeing Co.).

because of their aeroacoustic effects but each configuration does have specific configuration dependent characteristics.

In general, there has been too little research effort focused specifically on the aeroacoustic effects of propulsion airframe integration. These aeroacoustic effects are referred to as Propulsion Airframe Aeroacoustics (PAA). From a technology development point of view, the limited consideration of PAA has largely been the result of limited prediction method capabilities, limited computational resources, and the more complex experimental approaches required to address fully integrated systems short of full scale flight experiments. As such PAA represents an area of opportunity to develop noise reduction technology. This opportunity includes both reducing the noise sources that arise specifically from integration of propulsion and airframe and also using the installation itself as a means to reduce noise from a particular airframe or propulsion source. The value of this opportunity is amplified by the implication of Fig. 1 that new increments of noise reduction are becoming more difficult to develop. Considering a longer range horizon, using the configuration itself to maximize net radiated noise reduction also represents a key opportunity to develop technology that will enable the next 20 dB of noise reduction.

II. PAA Classification Tree

In general, the aeroacoustic effects related to propulsion airframe integration, or PAA effects, can be classified in various ways. The following classification, illustrated by the PAA Classification Tree in Fig. 2, begins with a fundamental division of PAA effects into those having to do with flow interaction and those having to do with acoustic propagation. Despite this distinct classification, it is however important to remember that in many cases these are not entirely unrelated issues. With these two fundamental divisions, the classification can then be extended to the next level. For flow interaction, the next important division regards the flow direction, upstream or inlet, and downstream or exhaust. Since turbo machinery and jet noise sources have different characteristics, acoustic propagation effects are more importantly divided along noise sources. The next lowest level of the classification tree is composed of identifying interactions between general engine and/or airframe components. Finally, some specific interactions are given along with key parameters. The classification tree shown in Fig. 2 represents a general way of organizing PAA effects. However, at the same time, the tree is not meant to imply that these effects can necessarily be studied or addressed separately.

Flow interaction effects are caused by the flow field around one component interacting with another specifically because of the location or orientation of installation. An example of this is the influence of the engine mounting pylon on the core jet exhaust flow. The influence of the pylon creates flow features in the jet that are not present in an isolated jet. These features are then also influenced by aircraft attitude. Another example is the interaction of the fan or core jet exhaust flow with an extended flap. This interaction is often present on Engine-Under-Wing configurations. These types of flow interaction effects from installation can create new acoustic sources or they can modify existing acoustic sources already associated with components.

Acoustic propagation effects arise when noise generated from various components propagates and interacts either with structure or with the flow over the airframe or from a propulsion device. The acoustic propagation of fan noise along the exhaust duct, for example, is altered by the presence of the bifurcator and pylon. Furthermore, the propagated fan noise can be scattered off deployed flaps and the effects can be different compared to the propagation of fan noise in isolation. Reflection of jet noise from the underside of the wing for the typical Engine-Under-Wing configuration is another example. These acoustic propagation effects are unlikely to create new noise sources specifically due to the installation; however, they can conceivably modify existing component noise sources. An example of this modification could be the reflected jet noise interacting with the jet noise sources.

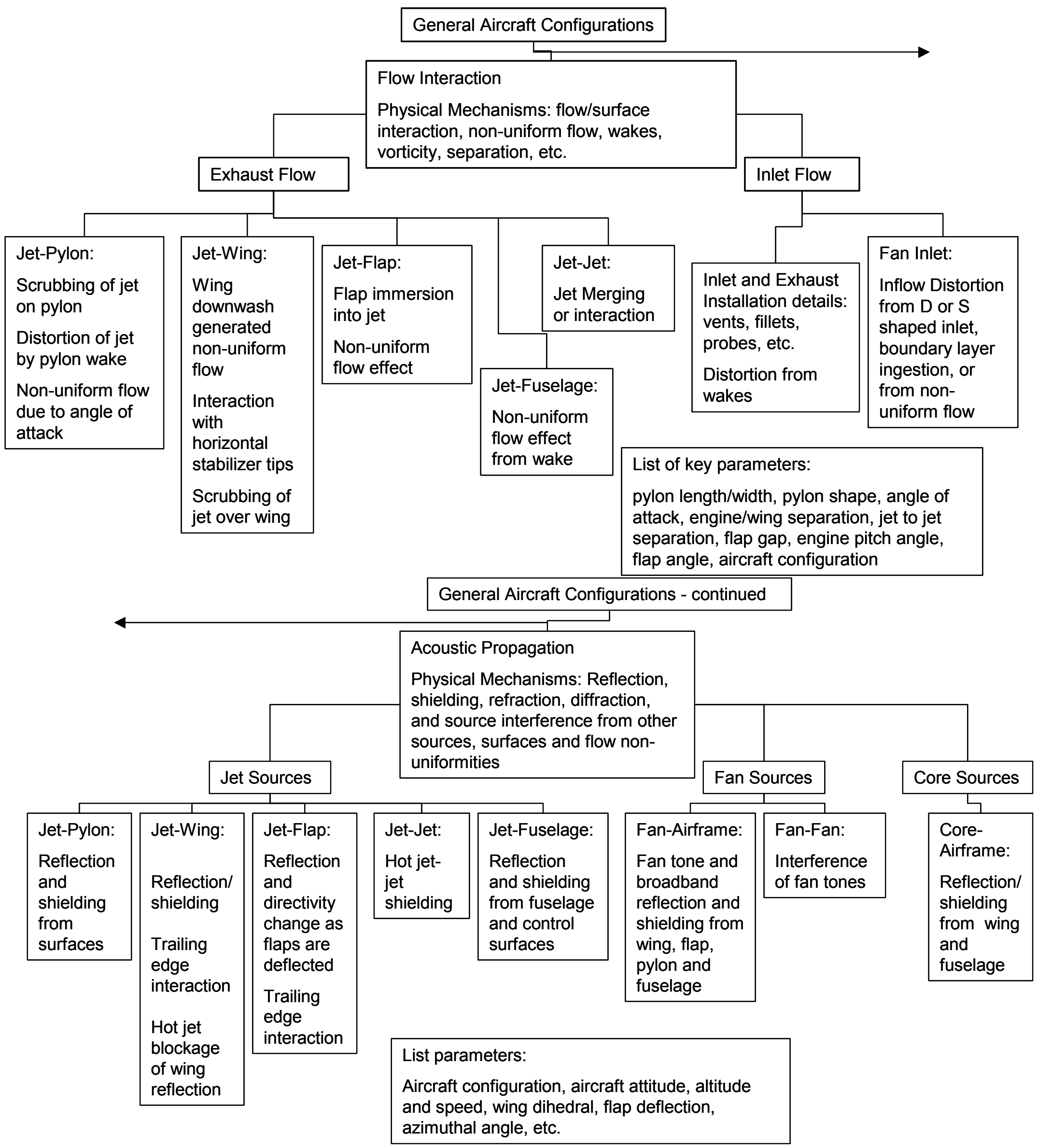

Figure 2. PAA Classification Tree

III. Promising Opportunity for PAA Noise Reduction: Airframe Shielding of Engine Noise

A. Airframe Shielding

The type and magnitude of PAA effects of an aircraft configuration will be dependent on the specific configuration and propulsion airframe technology used. In general, if a major design goal for a new transport is a significantly lower community noise impact, acoustic propagation effects should be considered in the configuration layout. These effects can include reflection, scattering, and shielding of propulsion noise sources by the airframe and flow interactions stemming from highly integrated configurations such as, for an unconventional example, exhaust distributed over large portions of the wing.

Considering the general possibilities for significant noise reduction from unconventional aircraft, the most direct and promising from a PAA perspective is to use the airframe to shield engine noise from ground observers. This method promises effectiveness since the noise levels of multiple engine sources can be reduced together and the issue of source proportionalities does not arise. It is therefore of interest to examine how the engines could be integrated, the airframe shaped, and the configuration laid out such that maximum noise reduction can be achieved through airframe shielding.

B. Installations on Conventional Configurations

Different engine installations may be implemented on conventional transport configurations, each installation having its own PAA characteristics. As mentioned previously, two commonly seen in production are the Engine-Under-Wing installation and the Aft Fuselage installation. These two installations have many design advantages and disadvantages and the selection of one over the other in a conceptual design has generally been case dependent and the result of various trade studies.

Engine-Under-Wing installations are generally advantageous structurally in providing bending relief for the wing roots while the aircraft is aloft. Also, the passenger cabin is generally shielded from engine exhaust noise by the wing and maintenance is more convenient since the engines are at an easily accessible height. Aerodynamically, this installation is not as advantageous since the nacelles interrupt the flow over the wing and considerable attention must be paid to both the wing design and the nacelle positioning. In addition, ground clearance issues (particularly for high bypass engines), danger of foreign object damage, and the occasional need for flap cutouts are disadvantages. Aft Fuselage installations have more aerodynamically efficient wings but more wing structure is needed to withstand the bending loads. Maintenance is more difficult, sometimes requiring steps to reach the engines, and interior noise can be significant at takeoff for passengers sitting in the rear of the cabin.

There is a distinct PAA advantage of the Aft Fuselage installation, as compared to Engine-Under-Wing, as it allows partial shielding of inlet radiated fan noise by the wing. Smaller aircraft in particular, such as business jets, are generally configured such that the engine inlet is right above the wing's trailing edge, which is a more optimal placement for inlet shielding. The aft radiated noise sources (such as the fan exit, core, and jet) can also be partially shielded on the sideline by the fuselage. By contrast, Engine-Under-Wing installations leave the engine noise free to radiate, unobstructed, to ground observers and even reflect off the wing's lower surface. Although all these PAA effects are minor compared to the total engine noise, they can be significant. Giving more consideration to these effects in a design may therefore motivate more Aft Fuselage configurations in the future. Research is ongoing to assess in more detail the shielding and reflection aspects of Aft Fuselage and Engine-Under-Wing installations so that a more informative comparison may be made. Scarfing the exhaust duct and adding an advanced liner have also been proposed as possible PAA improvements to the Aft Fuselage configuration.

Engine-Over-Wing nacelle installations, such as the Boeing YC-14, Beriev Be-200, and VFW Fokker 614 for example, have been employed operationally. These installations in general have two major noise advantages. One is the fact that an Engine-Over-Wing installation can allow the trends of higher bypass ratio and increasing fan diameters to continue without encountering ground clearance limitations. As has been discussed, bypass ratio increase has traditionally been the means by which both engine efficiency and noise have been improved and it is still a strategy that will likely be employed for the foreseeable future. The other advantage of Engine-Over-Wing installations is the potential for shielding of aft radiated noise sources by the wing. This shielding will be particularly effective for future high bypass turbofans since the noise signatures of these engines are expected to be increasingly dominated by aft radiated fan noise produced by highly loaded wide chord fan blade designs.[2]

Despite these inherent noise advantages, Engine-Over-Wing installations have traditionally suffered from poor cruise aerodynamics and have therefore rarely been favored over Engine-Under-Wing installations. Recent study[3] however suggests that proper wing design and nacelle placement can result in a significant improvement and even lead to a configuration with drag comparable to an Engine-Under-Wing installation. Figure 3 shows an example of such an Engine-Over-Wing configuration that was developed by Kinney et al.[3] The nacelles are located over the wing on a slipper mount and blow the jet exhaust over the upper surface. The twist distribution is optimized for minimum induced drag. The inboard portion of the wing is extended forward such that a large channel is formed between the nacelle and fuselage. This channel accelerates the flow, which creates increased suction over a large forward facing area and counteracts the drag penalty from nacelle interference. Proper airfoil tailoring can potentially minimize the strong shock and subsequent separation that would usually be associated with the accelerated channel flow. Thus, the fuselage and nacelle interference effects are used in a favorable manner. Cruise drag results of this configuration were obtained using a 3D unstructured full potential and integral boundary layer analysis and are summarized in Ref. 3. The results indicated that the Engine-Over-Wing configuration actually had slightly less drag at its design cruise Mach No. than the Engine-Under-Wing baseline. Work at NASA is ongoing to reassess the cruise aerodynamics of this Engine-Over-Wing configuration using Euler and Navier-Stokes CFD analysis and also assess the scrubbing drag from the jet flow over the wing surface. Studies are also underway to determine the airframe shielding benefits of the configuration using an acoustic scattering code. Previous analytical studies performed by Berton[2] on a large quad Engine-Over-Wing configuration with advanced high bypass engines indicated significant community noise reductions. It is anticipated that continued positive results on the aerodynamics and aeroacoustics of this specially designed Engine-Over-Wing configuration will lead to increased interest in the installation.

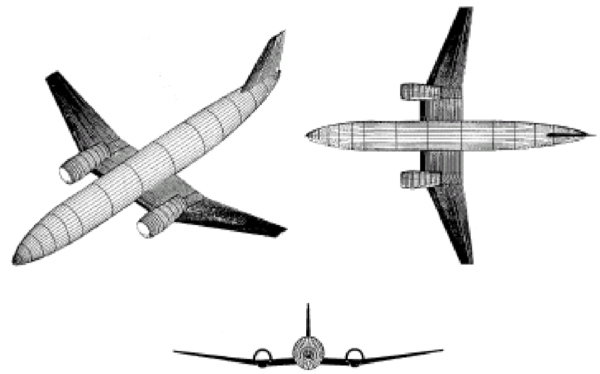

Figure 3. Advanced Engine-Over-Wing Installation.[3]

One other notional installation for conventional configurations, Engine-Over-Fuselage, is shown in Fig. 4. This installation offers some advantages over the configurations previously covered in that the longitudinal positioning of the engines and length of inlet and exhaust ducts are much less constrained. A large split duct containing both engines may be used rather than individual nacelles which could lead to lower skin friction and interference drag (assuming short inlet and exhaust duct lengths). Also, propulsion efficiency may be improved through ingestion of the fuselage boundary layer. Boundary layer ingestion, as will be described later, can yield a net benefit in propulsion efficiency through reduction of ram drag but requires control of inlet flow distortion. The centralized thrust axis would eliminate engine-out yaw and would allow smaller vertical tail surfaces and less rudder control power. Aeroacoustic advantages include shielding of the engine noise by the fuselage and also by longer inlet and exhaust ducts. Utilization of a V or U-tail can enable the jet exhaust to pass over the aft airframe.

Despite these advantages, designing the Engine-Over-Fuselage configuration to be competitive performance-wise with conventional Engine-Under-Wing or Aft Fuselage configurations will require careful consideration of the duct size. Although a long inlet or exhaust duct can be lined acoustically and provide significant attenuation of radiated engine noise, it will impose significant weight penalties and degrade propulsion efficiency, which are two highly undesirable effects on commercial transports. Two other technical challenges would need to be addressed for this installation to be considered. The first is the danger of placing both engines in close proximity to each other as an uncontained failure in one, such as a rotor burst, could threaten the operability of the other. The other problem involves the localization of all engine vibration above the passenger cabin as this could cause structural fatigue and increase interior noise to unacceptable levels. Consideration of this installation would therefore require careful study to determine what structure would be needed to acoustically isolate the

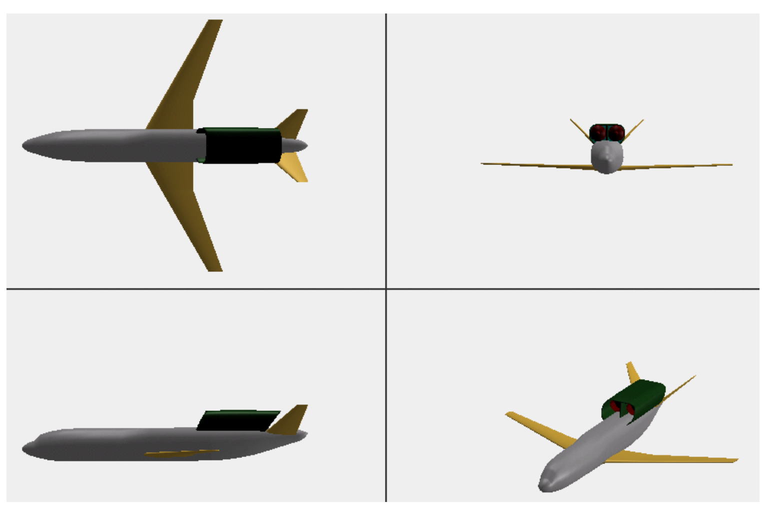

Figure 4. Notional Engine-Over-Fuselage Installation.

engines and what effect this structure would have on the aircraft weight and geometry. If the noise is indeed unacceptable, the concept could potentially be limited to a passenger/cargo combi transport where the cargo is placed underneath the engines.

C. Advanced Installations and Configurations

Despite the concepts mentioned above, conventional configurations generally offer only limited options for engine installations that can take advantage of airframe shielding. To more fully exploit this method of noise reduction, advanced configurations should be considered. One such configuration, offering both aerodynamic improvements and potential for more thorough airframe noise shielding, is a Blended-Wing-Body (BWB) shown in Fig. 5. Due to its expansive planform and over-airframe engine mounting scheme, the BWB offers significant shielding of forward radiated engine noise sources and potential for even more PAA optimal engine installations and configuration layouts.

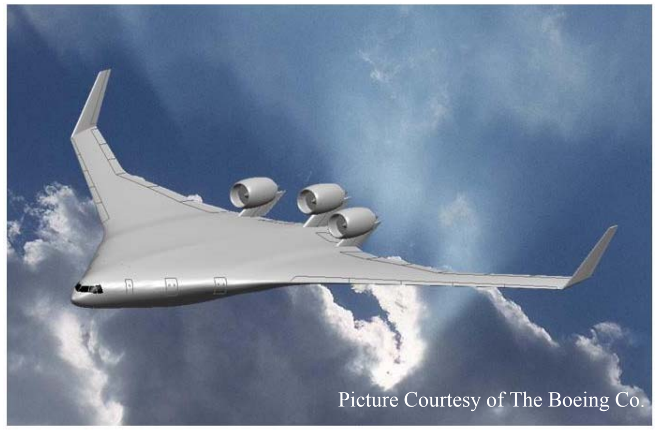

Figure 5. Blended-Wing-Body.

Acoustic tests were performed at NASA for the purpose of making preliminary assessments of the shielding capability of the BWB.[4] Figure 6 shows a BWB wind tunnel model that was used as the airframe shield. The engines were simulated by a fabricated generic broadband source and noise measurements were made on a microphone array in an acoustic chamber both with and without the presence of the airframe. From these tests, insertion loss maps, also shown in Fig. 6, were produced that display the source noise attenuation for each frequency as a function of the directivity angles. These maps show a substantial "shadow zone" in the forward quadrant where the source noise is attenuated by 20-25 dB overall for the higher frequencies and about 10 dB overall for the lower frequencies.[4] This data, though it does not include forward flight effects, indicates significant noise reduction potential and has also been useful in BWB community noise studies.

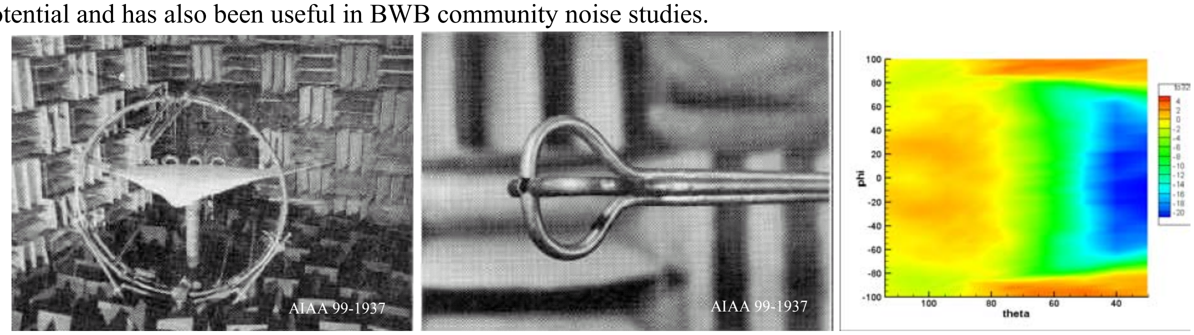

Figure 6. BWB Acoustic Shielding Experiments.

Full systems noise studies for a BWB have proved challenging due to the current state of the art in noise prediction tools. These tools generally rely heavily on empirical databases and have difficulty in analyzing advanced configurations like a BWB. Airframe noise in particular is very challenging to assess since not only is a BWB's airframe very different from conventional aircraft, but the approach angle of attack is much higher and the local flow characteristics around components are therefore different. It is also difficult to compute realistic takeoff and approach flight trajectories without the use of low speed aerodynamic data from the wind tunnel. Sizing studies, requiring component weight predictions, are also necessary to determine the correct engine size and throttling schedule.

Despite the shielding potential of a BWB, the airframe only provides substantial shielding of forward radiating noise sources. Aft sources, such as the fan exit, core, and jet, are neglected due to the trailing edge engine placement. It is therefore likely that the overall community noise benefit of a BWB will be small since observers will be fully exposed to the engine noise for the latter part of the flyover. This reality has motivated studies at NASA into ways of shielding the aft radiated sources. Unfortunately, moving the engines forward is not a very feasible option since the inlet location is largely constrained by the transonic shock line, which is roughly located at

75% chord. Reshaping the airframe or adding an aft extension are other options. Figure 7 shows an aft airframe extension concept for a BWB. This concept was studied by Hill et al.[5] to assess what noise reduction the extension could provide and also what systems impacts would be associated with its integration.

For assessing the noise reduction, a noise model was constructed of a GE-90-like engine using NASA's Aircraft NOise Prediction Program (ANOPP) and the model was calibrated using data from Gliebe.[6] Data from further shielding experiments at NASA were used to correct the GE-90-like model source predictions for the presence of the BWB airframe and different lengths of the extension. Figure 8 shows results for noise levels at the FAR-36 Cutback certification point (located under the takeoff flight path at 6,500 m from brake release) for a baseline BWB and two versions modified with extensions. The extensions are labeled "1-D" and "2-D" to indicate extensions of lengths equal to 1 and 2 engine fan diameters respectively. The results show modest reductions for the 1-D shield and very substantial reductions for the 2-D shield. This indicates that the effect of extending the aft airframe to shield the aft sources makes a significant difference on the total community noise levels.

Systems impacts to the BWB from addition of the extension were also assessed. Specific impacts include additional weight from the extension and skin friction drag from the increase in wetted area. Since the extension would only be needed for takeoff and landing, when noise reduction is most needed, the integration of a retractable extension, akin to a flap system, was considered as well. This would essentially eliminate the cruise drag penalty but would come at the cost of additional subsystem weight. To assess these impacts, a mission analysis was performed for a BWB with 2 GE-90-like engines. Appropriate assumptions were made to simulate the integration of the fixed and retractable extensions and the mission range was used as a measure of merit. Figure 9 shows the results. Modest drops in range are observed for the fixed extensions. For the retractable extensions however, the range penalties are less indicating that the increase in cruise drag was the most severe impact and the gain of additional subsystem weight does not offset the savings in range. A range vs. extension length curve for a configuration consisting of a retractable extension and embedded engines with boundary layer ingesting (BLI) inlets is also shown. As can be observed, the propulsive improvement of the BLI further offsets the penalties imposed by the extensions.

Figure 7. BWB With Aft Airframe Extension.

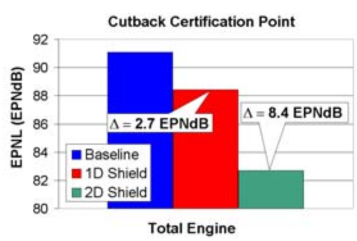

Figure 8. FAR-36 Cutback Noise Levels.

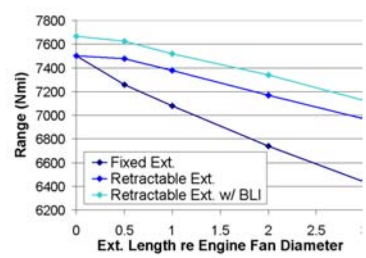

Figure 9. BWB Mission Range vs. Extension Length.

Despite its limitations in scope, the above study indicates that adding an aft airframe extension could provide a low cost means of substantial noise reduction. A potentially more desirable option however involves reshaping the BWB airframe such that the aft airframe noise sources are more effectively shielded, but that the total "amount" of airframe (which could be expressed as planform area, wetted area, or volume) is largely conserved. This redesign option would potentially restrict any weight or drag penalties to those associated with a sub-optimal planform shape rather than an increase of size. Figure 10 shows a notional planform modification superimposed over the current BWB planform that has area added to the aft end and area taken away from the wings. This modification would essentially give the BWB less of a wing and more of a fuselage. Figure 11 shows an early McDonnell-Douglas BWB[7] design which more reflects this line of thinking. Despite the conservation of the airframe size, aerodynamic penalties would likely still emerge with reshaping since the current BWB mold-line was largely optimized for maximum L/D and reshaping would upset this optimum. It is therefore apparent that finding a low noise BWB through airframe shaping with minimal or no adverse systems impacts will require a careful design study that uses Multi-Disciplinary Design Optimization (MDO) techniques with high fidelity tools to optimally balance cruise aerodynamics, propulsive efficiency, and aeroacoustics. Given the flexibility of the BWB planform, it is believed that such a well balanced solution is achievable and should be pursued.

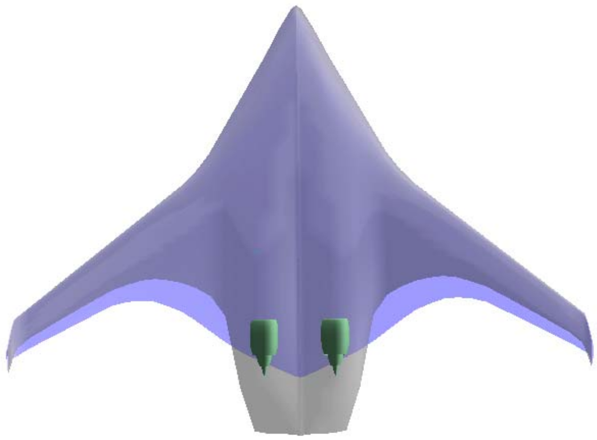

Figure 10. BWB With Reshaped Airframe.

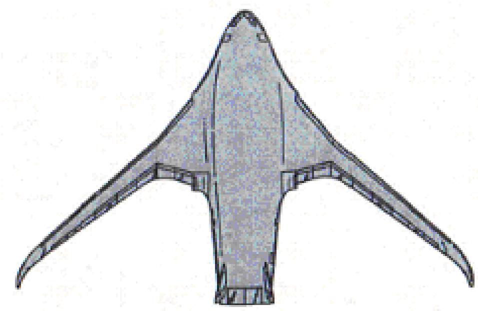

Figure 11. Early McDonnell-Douglas BWB Concept.[7]

One visionary propulsion concept that has been studied by various researchers and has potential for reduced noise is distributed propulsion. This concept involves replacing a conventional twin turbofan propulsion system with arrays of smaller gas turbine engines or electric fans. Figure 12 shows notional configurations employing distributed propulsion. The primary motivation for research of this concept is the desire to promote more synergy between the propulsion system with the vehicle aerodynamics, structure, controls, and high lift system. Using several smaller engines to power the aircraft enables flexibility in engine placement so that many of these synergistic effects may be realized. For example, by aligning an array of engines on the trailing edge of a wing surface, as shown in Fig. 12, the jet flow can be used to "fill in the wake" of separated trailing edge flow[8] and subsequently reduce drag. Passing the jet flow from embedded engines through a porous trailing edge can achieve the same effect and also yield a jet noise benefit.[9] Some engines with vectoring nozzles may also be used for control or high lift devices. Other engines may be solely devoted to powering on-board systems, which would eliminate the need to bleed primary engines. In addition to these benefits, weight reductions may also result from the manifestation of the square-cube law by which it may be postulated that since thrust reduces by length^2 and weight by length^3, smaller engines would have a higher individual thrust to weight ratio. It has also been suggested that economic advantages may be gained by employing a distributed propulsion powerplant. From a manufacturing perspective, mass production setups and workforce learning curves could potentially reduce the per unit cost of each engine. Small engines use less material and need smaller machines for their development than large engines, which also reduces the production cost. From a maintenance perspective, off-the-shelf replacement of engines could potentially replace the need for costly overhauls. The learning curve factor could also increase engine reliability. These theories however are still in need of investigation.

From a noise shielding perspective, the flexibility of integration that the concept of distributed propulsion offers

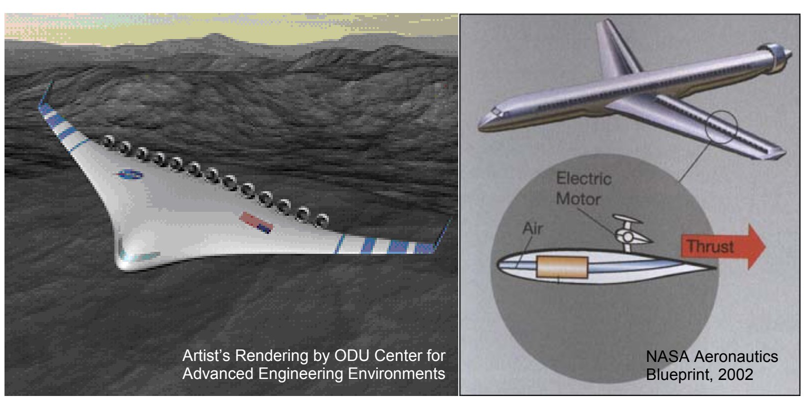

Figure 12. Notional Distributed Propulsion Concepts

leads to opportunities for significant noise reduction. Engines may be mounted in multiple locations and in areas not normally conducive to large turbofans so shielding of noise can be a more influential consideration in the configuration layout. Also, with a smaller engine, more of the inlet and exhaust radiated noise may be shielded with less airframe surface area. Using the engines for high lift and control in lieu of flaps and traditional control surfaces can also enable a clean airframe, which is advantageous for airframe noise reduction. Noise benefits associated with the size of the engines themselves were examined at NASA by Hill et al.[5] The jet noise was found to increase in frequency as the engine size decreased, but not enough to yield an atmospheric absorption benefit. Jet-to-jet shielding from a linear engine array may however offer some noise reduction.

Although many advantages to distributed propulsion including noise shielding may be envisioned, it is a much more complex powerplant concept and many technical challenges emerge whenever a specific configuration is considered. Although many broad top level studies of distributed propulsion have been performed, it is still largely uncertain how feasible or desirable the concept may be. Experience has shown that the concept should be assessed in the context of a specific configuration and significant consideration from a multi-disciplinary perspective must be given to all of the various integration aspects in order to determine how desirable the concept is compared to a traditional powerplant configuration. Such a concept, if highly favored, would also require many changes and developments in engine technology and current studies have therefore tended to be a bit far term and speculative. The economic questions mentioned earlier are also complex and concrete answers to them have thus far been rather elusive. Despite these difficulties however, it is still meaningful to consider the concept in the context of revolutionary low noise configurations, and further studies at NASA are therefore ongoing.

IV. Other Potential Opportunities for PAA Noise Reduction

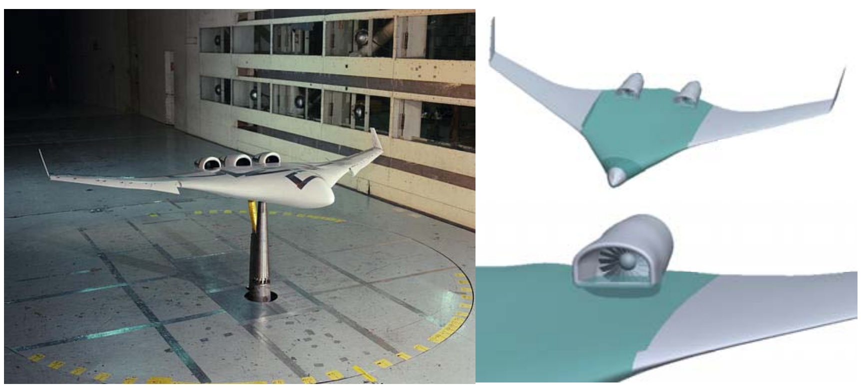

Figure 13. BWB With Boundary Layer Ingesting Inlets.

Although airframe shielding is here considered to be among the most promising of revolutionary PAA noise reduction concepts, others exist that are under study. One is boundary layer ingesting (BLI) inlets. Originally conceived for marine applications, the concept has also been given consideration for aircraft propulsion systems, most notably for the BWB. Inlet configurations are shown in Fig. 13. By ingesting the low momentum boundary layer off the airframe, ram drag is reduced yielding improvements in propulsive efficiency at cruise. These improvements are however offset by lower inlet pressure recovery and increased flow distortion. Passive and active flow control devices have therefore been studied[10] to minimize these penalties. From a noise perspective, BLI integrations offer potential opportunities for increased attenuation of inlet radiated noise due to the curved geometry of the S-Duct. The technology also enables engines to be embedded in the airframe without the configuration suffering drag penalties from boundary layer diverters. It is possible however that the increase in fan noise resulting from the flow distortion will offset these benefits. An analytical noise assessment of the technology has not yet been made. NASA and U.S. Air Force experiments are ongoing to better understand the noise levels of BLI.

Reducing aircraft noise through operations is an area of research that is receiving an increasing amount of attention. Improved operations allow an aircraft to move higher above the community during takeoff and landing and substantially reduce their noise footprints. Operations are particularly effective in that all noise sources are mitigated rather than just one or a few. Continuous descent approaches, characterized by elimination of the level flight segment before Instrument Landing System (ILS) intercept, have been studied and promise significant community noise benefits.[11] Continuous descent is also a near term operational solution as it can be performed by existing aircraft with modern avionics and adjusted air traffic procedures. Longer term operational solutions however could potentially include the use of aircraft with Short Takeoff and Landing (STOL) capability. Powered lift technologies therefore present another area of opportunity for significant noise reduction. By using the propulsion system to increase high lift capability at takeoff and landing, STOL operations, particularly steeper approaches, may be enabled. Of chief concern for aeroacoustics in a STOL transport however is the additional noise introduced into the system from larger engines, higher throttle settings, and jet-flap interactions. Developing a STOL transport that can enjoy the noise benefits of improved operations while minimizing noise penalties associated with powered lift is therefore a challenging design problem.

One promising pneumatic lift technology from a PAA perspective is circulation control,[12] shown in Fig. 14. This technology achieves high lift by blowing air from a thin slot near the wing trailing edge and turning the flow over a curved surface via the Coanda effect. Circulation Control technology has been in development for over three decades and has even been flight tested by the U.S. Navy. Much work has been done on the development of circulation control airfoils and some systems studies have been performed that examine the technology's integration onto a subsonic transport to replace conventional flap systems.[13] These studies have indicated the technology's ability to enable improved takeoff and landing performance and STOL capability. Aeroacoustics work has also been performed by Munro et al.[14] and has produced evidence, at the laboratory level, that a circulation control wing could even be quieter than a wing with a conventional flap system producing the same lift. These results are very encouraging in light of the concerns over the potential compromises to the noise benefits imposed by an additional powered lift source.

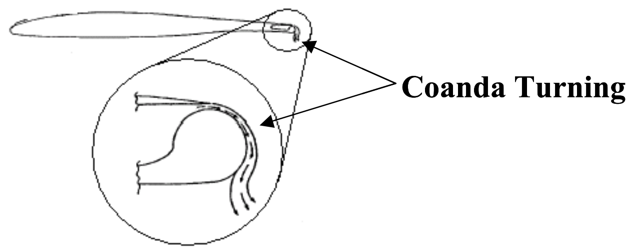

Figure 14. Circulation Control High Lift Concept.

Studies are ongoing at NASA to assess what noise benefits might be possible from a circulation control modified transport. Using Bombardier CRJ-700-like and Boeing 777-like aircraft models as baselines, dual radius flap airfoil data is being used to develop low speed aerodynamic models that will be used to compute achievable final approach trajectories characterized by descent angles exceeding the standard 3 degrees. Noise models are also being developed to assess the improvements in the community noise. In addition to standard approaches with increased slopes, the Simultaneous Non-Interfering landing approach[15] will also be examined. This approach, pictured in Fig. 15, is being studied by NASA and is designed to allow futuristic STOL regional jets to operate from shorter commuter runways simultaneously with larger aircraft operating on the main runways and relieve congestion at airports. The operation is characterized by an initial approach from 5,000 ft altitude and then a descent along a helical trajectory with a constant sink speed. In addition to enabling simultaneous non-interfering operations with the main runways, this trajectory is also designed to better localize the noise footprint within the airport exclusion zone. Due to the slow descent speed and tight maneuvering required, the operation is intended for an aircraft with STOL capability.

Two critical issues that need to be addressed in the assessment of circulation control aircraft are how the propulsion system will need to be designed and how much noise will come from the slot blowing. The noise signatures of aircraft are dependent on the size of the engines and very sensitive to throttle settings and it is important to know to a fairly certain extent how both the thrust and lift requirements will affect the propulsion system design and operation. Despite the encouraging aeroacoustic results from Ref. 14, a noise model of the "circulation control source" will also need to be developed in order to assess its impact on the total aircraft noise signature. Consideration of both these issues will allow the noise tradeoffs previously discussed to be properly examined.

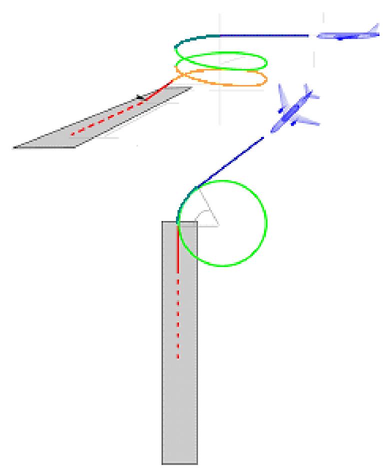

Figure 15. Simultaneous Non-Interfering Approach Trajectory.[15]

V. Challenges Associated With the Development of Advanced Configurations

It has been stated that advanced aircraft configurations present a promising avenue for revolutionary PAA noise reduction. Many of the PAA noise reduction opportunities heretofore discussed would require major changes to existing transport aircraft configurations and propulsion design in order to be implemented. These new configurations and designs will require noise considerations to be at the forefront of primary design drivers, which is a role noise has traditionally not played. These opportunities will therefore likely face many challenges in their eventual implementation. It is the authors' observation that major sources of these challenges include the high development costs of commercial aircraft, the long success record of conventional transport configurations, and the frequent conflict of noise with traditional aircraft value metrics.

Since the development of the first swept-wing jet-powered civil transports in the 1950's, the gross configuration has not changed significantly. This persistence of what is commonly referred to as the "tube with wings configuration" or the "707-DC8 paradigm" has led to recent speculation as to whether or not a major configuration change may be expected in transport design. This question was largely the initial impetus for the McDonnell-Douglas (later Boeing) and NASA Blended-Wing-Body studies[7] that occurred in the last decade. The intended application of the BWB concept has recently moved to military applications however. It can be argued that high development costs strongly influence transport aircraft configurations to retain their traditional form. Launching a new transport program is a multi-billion dollar effort drawn out over many years and gambles the airframer's entire financial future. Minimization of development cost and risk are therefore paramount in such a business environment. Revolutionary changes to the gross configuration significantly increase development costs since past experience and design databases cannot be fully utilized and new research must be performed to understand the performance and the trades in the design. Manufacturing costs also increase as facilities and tooling must be built or modified to develop a new type of airframe. In some cases, regulations and infrastructure must be modified to accommodate the aircraft into the air transportation system. Passenger acceptance must be reassessed if the configuration looks substantially "unfamiliar". Risk is increased for advanced configurations, partly due to the uncertainty in characterizing the design in the early conceptual phase when, according to Roskam,[16] about 90% of an aircraft's life cycle cost is determined. In this phase, analysis is not as detailed and low fidelity tools are generally used to predict performance. Many of these analysis tools are empirical and rely on databases of conventional aircraft. Moving outside these databases lowers accuracy and increases uncertainty at a time when knowledge of the aircraft's likely performance and potential design "show stoppers" must be as certain as possible. Although a new transport aircraft program necessarily involves the development of many advanced technologies in order to capture market segments from older aircraft, it is generally much easier to infuse the technologies into a conventional configuration concept that has been tried and true.

Another possible reason that conventional configurations have not been supplanted is their long success record. Although not optimal in many respects, the conventional wing and fuselage configuration satisfies a broad range of performance, operational, safety, and infrastructure requirements and any major departure from these designs nearly always results in trade-offs and compromises accompanying any improvements. This reality often becomes apparent when analyzing many advanced configurations from a systems perspective.

Finally, there are challenges associated with placing a large emphasis on noise in an aircraft design since lower noise, unlike lower weight or drag for example, often does not correspond to better efficiency and lower cost which are the contemporary value metrics of civil transports. Thus, if meeting certification or local airport standards is not a concern in a new transport design, it is imperative that noise technologies and design concepts do not lower efficiency or add cost. Many of the PAA concepts previously described have required, or will require, careful study to assess their systems impacts and verify that any trade-offs are minimal. The notable exception where lower noise does correspond to better efficiency is the high bypass turbofan and this characteristic has historically been exploited with great success. For revolutionary noise reductions to occur, more technologies and design concepts must be found that do not compromise the aircraft's value but improve upon it.

For the reasons discussed above, implementing revolutionary PAA design improvements that require departure from conventional configurations will be challenging. Increasingly stringent noise regulations and the growing importance of environmental friendliness however have begun to spark interest in more revolutionary designs as advanced technology on conventional configurations is expected to produce increasingly diminishing returns. Another factor that will possibly facilitate development of advanced configurations in the future is the growing capability of systems analysis in the conceptual design phase. Revolutionary improvements in computing power have allowed high fidelity analysis such as Computational Fluid Dynamics and Finite Element Analysis to be used in conceptual design. Developments in Multi-Disciplinary Design Optimization methods have also allowed more integrated analysis to be performed of entire systems in a single design framework. Development of probabilistic analysis has also allowed greater quantification of uncertainty and knowledge of risk. These further developments in the way design is conducted should allow more unconventional configurations to be seriously examined during conceptual design, provide greater confidence in results, and give designers in the future more flexibility in finding a low noise, well performing, and efficient configuration.

VI. Conclusion

Propulsion Airframe Aeroacoustics through advanced engine installations and configurations has been offered as a promising avenue to achieve significant noise reduction. PAA was further defined and the classification tree was presented. Airframe shielding of engine noise, catalogued under the "acoustic propagation" section of the classification tree, was identified as one of the most promising PAA opportunities and several research efforts at NASA were highlighted. It was argued that Aft Fuselage engine installations had PAA benefits compared to Engine-Under-Wing configurations and giving PAA more influence could motivate more of these designs. Engine-Over-Wing configurations were also discussed and research efforts to improve the cruise aerodynamics were highlighted. A notional Engine-Over-Fuselage configuration was offered as a potential low noise concept. Research efforts in both assessing and improving the noise signature of a Blended-Wing-Body were discussed. It has been found that airframe extensions could be a low cost means of significant noise reduction and it was suggested that airframe reshaping could be a more effective means of shielding aft radiated engine noise sources. Distributed propulsion was offered as a revolutionary aero-propulsive concept with significant potential for low noise PAA design. More study in this area is however needed. Boundary layer ingestion and Circulation Control were offered as additional, non-shielding related, PAA opportunities and current research efforts were highlighted. Finally, attention was given to the challenges that would be associated with developing many of the advanced engine installations and configurations presented. It was argued that high development costs, the long success record of the conventional wing and fuselage configuration, and the frequent conflict of noise with traditional aircraft value metrics are major reasons why the gross configuration of transport aircraft has changed little.

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