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Military Aviation and the Environment: Historical Trends and Comparison to Civil Aviation

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Trends in the environmental impact of military aviation between 1960 and 2000 are articulated. The focus is on community noise, local air quality, and global climate impacts and the discussion is restricted to fixed-wing aircraft. Comparisons are made to trends within the commercial air transport industry. The unique features of military aircraft technology and operations responsible for the differences in environmental impacts are described. The discussion also considers the effects of environmental restrictions on the deployment and combat readiness of military aviation services. Regulations designed to mitigate environmental impacts from military and civil aviation are also reviewed. The analysis shows that military aviation has been responsible for a small and decreasing fraction of total fossil fuel use in the United States. Furthermore, when averaged nationally, contributions to local air-quality impacts and community noise have decreased over the period considered. These trends are a result of historical reductions in fleet sizes and number of operations. However, because base closures were largely responsible for these reductions, the impacts at any given installation may not reflect overall trends. Community noise and air quality are expected to be a growing concern for military aviation due to increasing urbanization, increasing public and regulatory attention, and use of training spaces for larger, multiservice operations involving longer range, higher speed weapon systems.

I. Introduction

IN the United States, environmental concerns have increasingly focused on the impacts of aircraft operations. This reflects a decrease in public willingness to accept environmental deterioration, improved identification of aviation contributions (which generally increase with growth), and a better understanding of the ways health and welfare might be affected. To effectively balance needs for mobility with demand for environmental protection, actions in the commercial arena must address a wide range of scientific, design, and policy problems that require joint attention to noise, air-quality, and climate issues. Military aviation faces an equally complex challenge in balancing these issues against national security needs. This paper describes the technological and operational factors that characterize military aviation impacts. It provides an assessment of the current scope and magnitude of environmental effects and the present policy approach. Our goal is to contribute to a more effective balancing of environmental and national security objectives.

Our analysis concludes that, when averaged nationally, noise and emissions impacts associated with military aviation have generally declined in the United States. However, local circumstances have resulted in discrete areas of increased impact and it is these local issues that are likely to define future pressures for environmental progress. Section II begins by discussing current regulatory measures used to control health and welfare impacts, along with examples of the tradeoffs imposed on military operations. Section III reviews the pathways through which noise and emissions produced by aviation operations are currently understood to result in environmental change and identifies relevant metrics. Section IV employs these metrics to evaluate the historical evolution of community noise, local air quality, and global climate impacts associated with military aviation. Section V is a summary.

Unique features of military aircraft technology and operations are responsible for differences in environmental performance when compared to commercial aviation. It will be apparent from our investigation that data and methods for quantifying trends in environmental impact are more readily available than complementary information for quantifying how environmental requirements affect national security. Because the lack of such a capability makes it difficult to fully evaluate this important interaction, we recommend an effort to establish metrics for assessing national security impacts. This is an important challenge for the U.S. Department of Defense (DoD), the agency ultimately responsible finding the right balance.

II. Context of Military Aviation Environmental Impacts

The most important impacts of environmental issues on military aviation are associated with the deployment and combat readiness of the airborne services, particularly as related to limitations on the realism of training activities.[1−3] Navy pilot training for aircraft carrier landings in the United States is a valuable example of the practical implications. Land-based training for carrier landings is intended to closely mimic actual procedures at sea. To best preserve realism, pilots would ideally execute such field carrier landing practice (FCLP) procedures from a 600-ft (∼185-m) pattern altitude to simulate an approach at sea. However, resulting noise levels in residential areas surrounding some bases have proved unacceptably high using this altitude. Naval Air Station (NAS) Oceana and Naval Air Landing Field (NALF) Fentress, the primary east coast training areas for navy pilots, raised FCLP procedures to 1000 ft (∼305 m) and 800 ft (∼245 m), respectively, gaining a reduction in noise levels, but also losing realism. Because this is a potential safety issue for operations at sea and may extend training requirements, the navy has recently launched an effort to identify a new remote outlying field at a potential cost of $40 million to $115 million to alleviate these operational impacts.[§]

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§Data available online at http://198.65.138.161/military/facility/fentress.htm [cited 6 May 2002].

Issues related to operational restrictions resulting from noise, such as the FCLP case, or air-quality concerns are broadly termed encroachment. Once remote and sufficiently large to minimize interactions with local populations, bases and training ranges have faced increasing pressure from local communities to mitigate environmental effects. Evolving DoD requirements for use of training ranges compound the effect of increasing urbanization. As the DoD pursues more multiservice, coordinated warfighting, and as the speed and range of sensors and weapons systems increase, the size of the battle space effectively increases. Thus, the area required for training increases.

While tort cases have long been a route for resolution of environmental grievances (nuisance complaints, for example), a significant basis of U.S. federal environmental and administrative law has been established over the past three decades that outlines the minimum extent to which encroachment is considered in decisions concerning military aviation. The broadest legal standard addressing the use of DoD environmental expenditures is the 1969 National Environmental Policy Act [NEPA; 42 United States Code (USC) 4332]. NEPA requires federal agencies to assess the health, socioeconomic, ecological, cultural, and aesthetic impacts of major actions through the development of an environmental impact statement (EIS). NEPA has an important role in weapon system basing decisions.[4] Although it is not possible to generalize which issues will be most important in any particular EIS, recent assessments for the F/A-18C/D, F/A-18E/F, and F-22 aircraft suggest noise and emissions have increasingly influenced deliberations.[5,6] A national security exemption in the 1972 Noise Control Act (NCA; 42 USC 4901–4912) gives the EIS process and court actions based on constitutional and tort law a central role in responses to noise impacts. For example, property owners in Virginia Beach and Chesapeake, Virginia, have alleged that overflights of navy F/A-18C/D aircraft have adversely impacted the value of their property and have resulted in a taking without compensation, in violation of the Fifth Amendment of the U.S. Constitution.[6] The regulatory treatment of military aviation emissions is broader. Unlike noise, federal law provides states with an important additional measure of control over the emissions of military aircraft through the general conformity rule of the 1970 Clean Air Act (CAA; with amendments, 42 USC 7401–7601).

The CAA provides for minimum air-quality standards for certain pollutants (the National Ambient Air Quality Standards, or NAAQS) and requires states to implement a plan to achieve or exceed these minimum standards. Although there are no direct emissions regulations for military aviation technology, the general conformity rule (42 USC 7506) prohibits the federal government from funding, licensing, permitting, approving, or otherwise supporting activities that do not conform to an approved state implementation plan (SIP). Any activities at a military installation or range that are not consistent with state plans can thus be halted. Conformity rule-based obligations were required for the F/A-18E/F introduction at NAS Lemoore in 1998, where the navy had to identify 300 tons ($\sim$270 t) of NO_x emissions offsets before the aircraft would be allowed to operate.[7] The Joint Strike Fighter may face similar restrictions as more than half of the bases considered for operations could be impacted by their presence in nonattainment zones, areas that do not meet the primary NAAQS set by the federal government.[8] The military has closed more than a dozen bases in California as part of the base realignment and closure process, and difficulty in attaining emissions standards was one of the many important factors considered. Commercial airports must also conform to an applicable SIP, and this indirectly influences certification standards for commercial aircraft emissions. A similar indirect connection to design practice is also apparent for military systems. Although there are no certification standards, manufacturers are increasingly considering environmental performance in their research, design, and development activities for military aircraft.

In fiscal year 2002, DoD was authorized to spend up to $4 billion in public funds for environmental programs [Public Law (PL) 107-107].[9] Although legal standards provide a means to resolve environmental complaints, military planning has historically emphasized land-use policy to manage local impacts associated with noise and emissions. Indeed, compatible land-use policies (along with enhanced administrative functions and improved community outreach) are the basis of the Sustainable Ranges Initiative[7] and the Readiness and Range Preservation Initiative,[3] the most recent DoD programs to balance environment and national security. The continued necessity for operational limitations and erosion of land buffers at existing sites, as well as negative effects on basing decisions for future systems, suggests that a different approach may be necessary in the future. Emissions and noise performance requirements may become a more significant part of military technology development. This may be particularly important in dealing with environmental issues that do not as yet have an institutionally defined standard of control. Although it is expected that the local noise and emissions issues overviewed in this section will remain central for several decades, climate issues represent an important source of uncertainty in establishing future military aviation environmental requirements.

Alternatively, to limit the perceived costs of environmental restrictions on military readiness, legislative remedies have been proposed that would require an explicit balancing of the environmental and national security requirements placed on military aviation. An early version of the 2002 DoD budget authorization bill (PL 107-107) would have required a national security impact assessment to be performed in parallel with the EIS. Although not passed into law, this proposal highlights the ongoing search for an improved methodology through which environmental and national security impacts can be comparatively assessed and balanced. The next sections demonstrate that data and methods for quantifying the environmental impact of military actions are available. However, complementary information for assessing the national security impact of various environmental actions, beyond anecdotal evidence, is comparatively lacking.

III. Metrics for Aviation Noise and Emissions Impacts

A variety of metrics are available for assessing the noise and emissions performance of aircraft and the civil and military systems in which they operate. Some are more useful for understanding trends in technology, whereas others have greater relevance to evaluating environmental impact. Our focus is on the latter. For example, noise levels are well correlated to the overall weight, number of engines, and the mission defined for an aircraft. When these factors are taken into account, as in commercial aircraft certification standards, technology trends are more clearly highlighted. However, from a community noise perspective, the person on the ground is less concerned with the configuration of the aircraft than with the perceived noise it produces. Thus, trends in environmental impact are more appropriately assessed using measures such as the effective perceived noise level (EPNL), independent of the weight of the aircraft. As another example, NO_x is a strong function of engine pressure ratio and the overall rated thrust output of the engine. Although technology performance is typically evaluated in terms of the mass of NO_x per unit thrust, placed on a sliding scale in terms of engine pressure ratio, local air quality is more directly related to the total mass of pollutants emitted (e.g., kilograms of NO_x per day). This section reviews the metrics used to judge the magnitude and scope of aviation emissions and noise impacts. Noise is addressed in Sec. III.A and emissions in Sec. III.B. Section IV addresses the underlying technological and operational trends.

A. Assessment of Noise Impacts

Although auditory damage is an important occupational hazard for aircraft support personnel, community noise levels around bases are not typically high enough to cause hearing loss. Noise in any case produces a variety of adverse physiological and psychological responses. Common among these are speech interference and sleep disturbance, which may result in reduced productivity for a variety of tasks associated with learning and work. Definitive evidence of other nonauditory health effects as a direct consequence of aviation noise is not available,[10] but some studies suggest such connections, including hypertension in children.[11] The most widespread measure of adverse reactions to living in noisy environments is annoyance, a generalized and subjective descriptor that by definition overlaps with the impacts already mentioned. There is a variety of well-established procedures and metrics for relating sound measurements to human annoyance. These take account of the nonuniform response of the human ear both in frequency and amplitude, sensitivity to tonal vs broadband noise, and levels of background noise. For a single aircraft operation these effects are usually represented by EPNL measured in decibels (EPNdB). For commercial aircraft, EPNL forms the basis of noise certification standards set under the NCA and subsequent amendments. The EPNL signature of a military aircraft is controlled primarily by engine noise. Studies have also attempted to determine the impact of aircraft noise on over 100 different species of domestic and wild mammals, birds, and marine mammals. The majority of the literature indicates that domestic and wild animals exhibit minimal behavioral reactions to military overflights and seem to habituate to the disturbances over a period of time without discernible long-term effects.[4] In the absence of definitive data on the effect of noise on animals, the U.S. National Research Council has proposed that protective noise criteria for animals be taken to be the same as for humans.[12]

For assessing the noise impact of a specific base on the local community, it is more useful to consider a summative measure of the noise produced by flight operations. One such measure is the day/night noise level (DNL), a metric correlated with community annoyance from aircraft noise. The DNL metric is calculated as the A-weighted sound energy (i.e., accounting for unequal loudness perception across different frequencies) averaged over a 24-h period. A 10-dB penalty is added for nighttime events, assuming that night operations are twice as annoying as those occurring at other times of the day because of the potential for sleep disturbance and because background noise is lower at night. The U.S. Federal Aviation Administration (FAA) and DoD employ DNL to determine the compatibility of airport-local land uses with aircraft noise levels. Table 1 summarizes community response to noise as described by DNL.[10] At 55 dB DNL (indoors or outdoors), a community will generally perceive aviation noise as no more important than various other environmental factors with about 3% of the population highly annoyed. At 65 dB DNL, 12% of the population may be highly annoyed and the community will generally consider aviation noise as one of the important adverse aspects of the environment. For comparison, the range of exposure to noise in urban areas is typically 58–72 dB. Corresponding ranges for suburban and wilderness areas are 48–57 dB and 20–30 dB, respectively.

It is important to note that, although the correlation in Table 1 is a useful gauge of community response, it does not necessarily determine when noise ceases to have an economic impact on a community (e.g., via property value depreciation). Noise-mitigation policies based on DNL implicitly perform a cost–benefit balance, and current DoD and FAA noise planning policies suggest that areas with less than 65-dB DNL levels should not be considered for noise abatement. However, for both military and commercial aviation, most complaints regarding aviation noise come from areas with a DNL less than 65 dB. Data compiled by the FAA to evaluate extent of population exposure to commercial aircraft noise levels at or above outdoor urban environments indicate that the number of people living in areas with a DNL of 55–65 dB may be 5–30 times the number of people living with greater than 65 dB DNL. Figure 1 shows the historical evolution of noise exposure in these zones and future projections developed by the FAA. The large reductions in the population affected by commercial aviation noise indicated by Fig. 1 have resulted primarily from two factors: low-noise aircraft operations enabled by advances in aircraft communication, navigation, and surveillance, and air traffic management technology, and the phase-out of high-noise aircraft through regulatory action enabled by the availability of improved engine technology (e.g., as increased bypass ratio). The importance of the latter, made possible through international agreement and enacted through the 1990 Airport Noise Control Act (49 USC App. 2151–2158), is quite significant. Although the total number of aircraft phased out corresponded to 55% of the fleet in 1990, that portion of the fleet accounted for more than 90% of the total cumulative noise at airports. The cost of prematurely retiring these aircraft has been estimated at between \$5 billion and \$10 billion.[13,14] Over the next 20 years, estimates by the FAA suggest that the number of people affected by commercial aircraft noise in the United States will be constant; increases in the number of operations are expected to offset projected improvements in technology within the fleet. To address continued noise concerns, the FAA has adopted a "balanced approach"—a combination of source reduction (quieter aircraft), land-use planning and management, noise abatement operational procedures, and operating restrictions.

The DoD assesses noise exposure at individual military bases using similar modeling techniques as the FAA for commercial aircraft. No overall exposure data is available for the military case, but an example comparison between the military and commercial experiences with noise exposure can be found in the map shown in

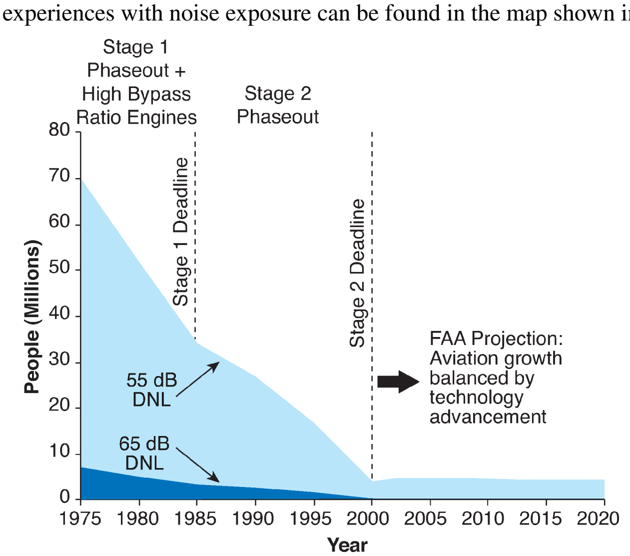

Fig. 1 Estimated number of people exposed to commercial aircraft noise in the United States.[28] Noise exposure for 65-dB DNL to 1996 estimated from historical FAA sources. Future estimates calculated using the FAA MAGENTA noise model. Exposure to 55-dB DNL is based on scaling from current population distributions around airports.

Table 1 Residential response to noise levels described by the DNL measure[10]

Effects: hearing loss annoyance				
Day night average sound level, dB	Qualitative description	Population highly annoyed, %	Average community reaction	General community attitude toward area
75 and above	May begin to occur	37	Very severe	Noise is likely to be the most important of all adverse aspects of the community environment
70	Will not likely occur	22	Severe	Noise is one of the most important adverse aspects of the community environment
65	Will not occur	12	Significant	Noise is one of the important adverse aspects of the community environment
60	Will not occur	7	Moderate to slight	Noise may be considered an adverse aspect of the community environment
55 and below	Will not occur	3	Moderate to slight	Noise considered no more important than various other environmental factors

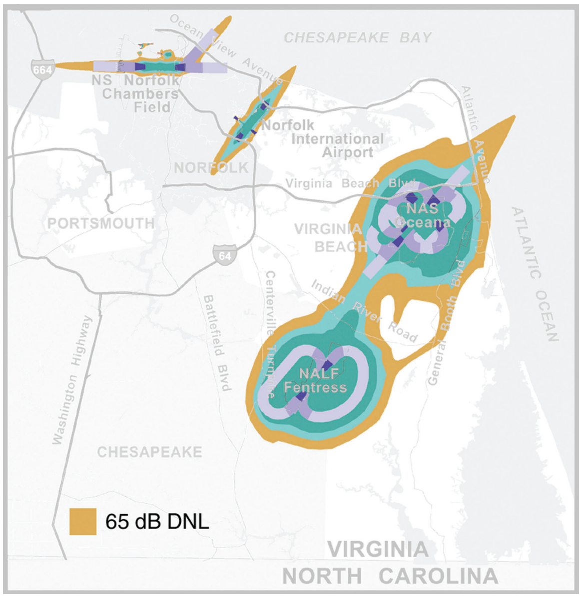

Fig. 2 Noise exposure mappings of DNL contours for NAS Oceana, NALF Fentress, and Naval Station Norfolk Chambers Field with comparison to Norfolk International Airport. Compiled by the DoD Air Installations Compatible Use Zones program using the NOISEMAP model.[17] Image data provided by J. Ghosen, Ecology and Environment, Lancaster, NY, 2001.

Fig. 2, which includes three military airfields and one commercial airfield. NAS Oceana and NALF Fentress have perhaps the most significant community noise opposition of any military airfields. FCLP procedures conducted at these bases represent particularly noisy operations, reflected in the extent to which the 65-dB DNL contours reach into the local community. In comparison to Norfolk International Airport, the land area exposed to 65-dB DNL or higher around Oceana is greater by approximately 10 times. Approximately 87,000 people reside within the 65-dB DNL contours around Oceana and Fentress alone.[15] In comparison, the FAA estimates that, cumulatively, approximately 500,000 people reside within the 65-dB DNL contours around all commercial airports in the United States.[16] A balance between number of operations and the noise level of the related technology explains the difference in exposure area. There are only ∼120 takeoffs per day at Oceana compared to the average 210 takeoffs per day at Norfolk.[¶] However, military aircraft can be significantly noisier than their commercial counterparts. These technological and operational trends are further elaborated in Sec. IV. The large contours around Fentress, built to move FCLP operations from Oceana, are the result of an average of 354 FCLP and 20 takeoff operations per day[17] and reflect the modified, higher altitude FCLP procedures discussed previously. As noted, military aviation has typically relied on operational changes and land-use planning to address these noise concerns.

B. Measurement of Emissions Impacts

Emissions impacts are distinct from noise impacts for a variety of reasons. These include a more direct connection to human and ecosystem health (e.g., morbidity and mortality versus annoyance), a broader range of time scales over which the effects can occur (from a day to hundreds of years), and a broader range of length scales over which the effects are realized (local, regional, and global). As a whole, aviation emissions are expected to increase and constitute a greater proportion of both the local contributions to regional emissions around airports and the global anthropogenic climate impact.[18,19]

The total mass of emissions from an aircraft is directly related to the amount of fuel consumed. Chemical species in the exhaust that are of consequence to emissions impacts include carbon dioxide (CO_2) and water vapor (H_2O), nitrogen oxides (NO_x), unburned hydrocarbons (UHCs), carbon monoxide (CO), sulfur oxides (SO_x), other trace chemical species that include the extended family of nitrogen compounds (NO_y), and nonvolatile particulate matter (PM). Emissions of CO_2 and H_2O are products of hydrocarbon fuel combustion and are thus directly related to the aircraft fuel consumption, which in turn is a function of the weight, aerodynamic design, and engine performance of the aircraft. Emissions of NO_y, nonvolatile PM, CO, UHCs, and SO_x are further related to the manner in which fuel is combusted within the engine and, to some extent, to postcombustion chemical reactions occurring within the engine. PM and UHC emissions are additionally dependent on fuel composition. Thus, emissions other than CO_2 and H_2O are primarily controlled by the engine design, but total emissions can be reduced through improvements in overall fuel efficiency. Such emissions are therefore typically quoted relative to the total amount of fuel burned as an emission index (e.g., grams of NO_x per kilogram of fuel).

Local air-quality issues around airports focus on the human health (e.g., cardiac and respiratory) and welfare (e.g., visibility and acidic precipitation) impacts of ozone production, related to emissions of NO_x, CO, and UHC, and changes to ambient concentrations of fine particulates, due to direct perturbations from nonvolatile PM emissions and secondary formation of volatile PM resulting from conversion of NO_y, SO_x, and possibly UHC emissions. The NAAQS determined by the U.S. Environmental Protection Agency set limits on ozone and two size ranges of PM; less than 10 μm (PM10) and less than 2.5 μm (PM2.5). Aviation-related PM emissions are found in the smaller size range. The remaining NAAQS address CO, SO_2, NO_2, and lead. Additional chemical species emitted from aircraft engines have relevance to climate change.[18] Climate change is also associated with a broader range of impacts on human and ecosystem health and welfare.[20]

Assessments of aviation contributions to local and regional emissions inventories and how they may alter air quality are lacking for military aviation. Furthermore, in contrast to noise assessments, few metrics have been developed to evaluate population exposure to airport air-quality impacts. Airport NO_x, UHC, and CO emissions, which result from a combination of both aircraft- and non-aircraft-related ground operations, can be important contributors to regional ozone levels. One example is shown in Fig. 3, which compares the NO_x contributions of Kennedy and LaGuardia airports around New York City to major point sources in the region.[21] In many regions, airports are among the single largest sources with contributions to regional emissions inventories that are typically several percent of the total.[19] For many air-quality changes, a direct proportionality between emissions and ambient concentrations can be assumed as a first-order estimate of impact.

Health and ecosystem impacts associated with climate change are related to alterations in surface temperatures, which vary regionally and occur as the result of perturbations to the radiative balance

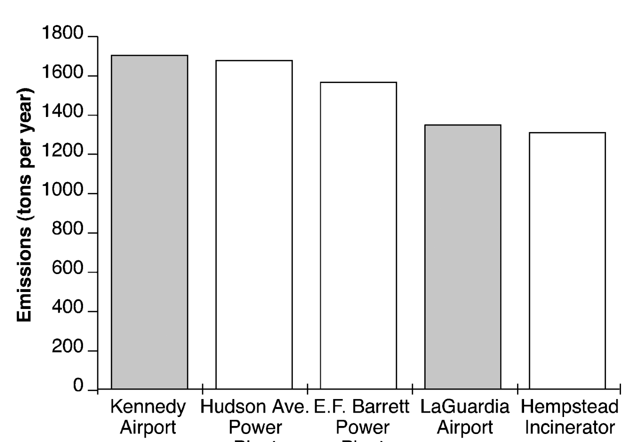

Fig. 3 Ranking of top sources of NO_x emissions for the New York City metropolitan area.[21]

¶Data available online at http://www.norfolkairport.com/faq_answers2.html#planes [cited 9 June 2004].

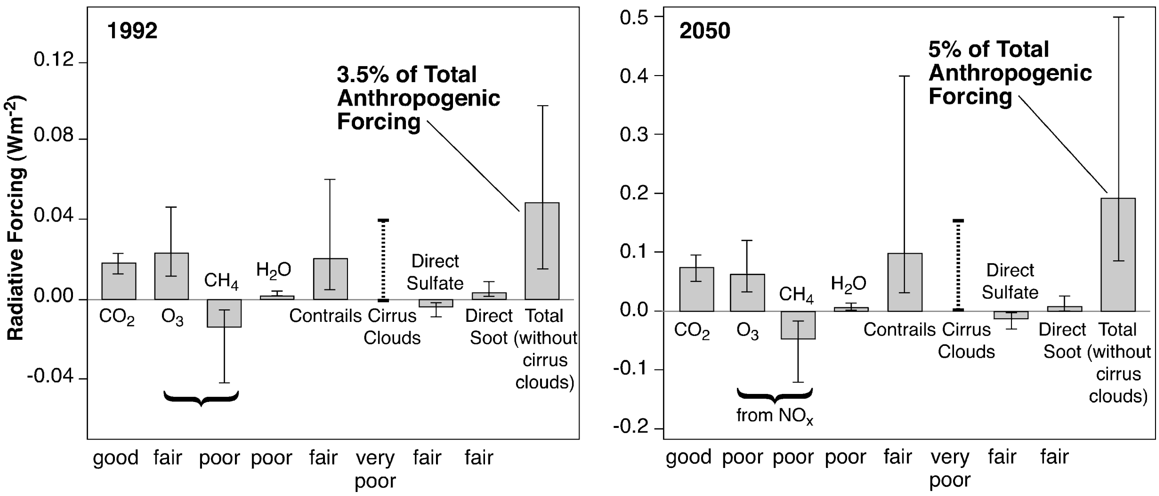

Fig. 4 Aircraft radiative forcing estimated for 1992 (+0.05 W/m^2 total) and projected to 2050 (+0.19 W/m^2 total).[18] Note differences in scale. Notations below graphs indicate the level of scientific understanding for the impact of each exhaust species. The heavier dashed bar for aviation-induced cirrus cloudiness describes the range of estimates, not the uncertainty.

of the atmosphere. Changes in this balance are communicated in terms of radiative forcing, measured in watts per unit of surface area (e.g., watts per square meter). Positive radiative forcing indicates a net warming tendency and is typically determined relative to preindustrial times. Because the majority of aircraft emissions are injected into the upper troposphere and lower stratosphere (typically 9–13 km in altitude), aviation emissions impacts are unique among all industrial activities. The impact of burning fossil fuels at altitude is approximately double that due to burning the same fuels at ground level. The mixture of exhaust species discharged from aircraft perturbs radiative forcing two to four times more than if the present day impact of only atmospheric CO_2 accumulation attributable to aviation is considered. This is largely a result of the relatively short-lived effects of NO_x and aviation-induced cloudiness (contrails and cirrus formation), although there is a high uncertainty with respect to the latter.[18]

Figure 4 shows recent estimates of the instantaneous radiative forcing in 1992 attributable to various aircraft emissions and projections for the year 2050 published by the Intergovernmental Panel on Climate Change (IPCC). This chart accounts for the present day impact of the full history of aviation emissions. These estimates translate into an estimated 3.5% of the total anthropogenic forcing in 1992 and 5% by 2050 for an all-subsonic commercial fleet. For both 1992 and 2050, it is estimated that there is a 67% probability that the value for radiative forcing falls (or will fall) within the range indicated by the error bars. Thus, for 2050, it is likely that the radiative forcing due to aircraft alone may fall between 2.5 and 13.2% of the total anthropogenic forcing. Although broadly consistent with these IPCC projections, subsequent research reviewed by the Royal Commission on Environmental Protection has suggested that the climate impact indicated in Fig. 4 is likely to be an underestimate.[22] In particular, although the impact of contrails is probably overestimated, aviation-induced cirrus clouds could be a significant contributor to positive radiative forcing, NO_x-related methane reduction is less than shown, reducing the associated cooling effect, and growth of aviation in the period 1992–2000 continued at a rate larger than that used in the IPCC reference scenario. The trends discussed in the next section will help assess the extent to which this potentially significant impact relates to emissions from military aviation.

IV. Trends in Military Aircraft Environmental Performance

In light of increasing demand for environmental protection and increasing requirements for range access[7] to maintain national security, it is valuable to assess trends in the environmental performance of military aviation systems. This section examines these trends and our analysis further reflects the evolution of military aviation noise and emissions characteristics against similar characteristics in commercial aviation to highlight the governing factors. Much of the public pressure to alleviate aviation environmental impacts derives from their experience with commercial aircraft.

The contrasting goals of military and civil aviation lead to systems designed for significantly different missions, and it is the performance and use of these systems, rather than fundamentally different mechanisms of noise or emissions production, that drive differences in operational and technological trends. This is particularly the case for high-performance military aircraft. Section IV.A briefly reviews the functional requirements of military and commercial aircraft and their effect on aircraft and engine design, noise, and emissions. Section IV.B discusses trends in fleet size and differences in operational tempo between military and commercial aviation. Following this, historical trends in noise and emissions are presented in Secs. IV.C and IV.D, respectively. Metrics of comparison were chosen to assess trends in technology as they affect environmental impact. Several data sources were used as inputs to the analysis including emissions and noise data,[23–29] fleet and operational statistics,[30–37] and descriptions of aircraft and engine parameters.[38–40] The analysis considers only fixed-wing aircraft.

A. Mission Aircraft Requirements, Effects on Design, and Implications for Noise and Emissions

Before discussing specific relationships between aircraft and engine design (and noise and pollutant emissions), some general observations regarding unique features of aviation systems relative to other modes of transport will help provide useful benchmarks. Compared to land-based systems, aviation systems are characterized by more stringent weight and volume constraints, and higher complexity, and safety is often a more critical issue in design and operation. These characteristics lead to very long technology development times (10 to 20 years) and high capital costs ($100 million for a commercial aircraft, and as high as $1 billion for some military aircraft). Furthermore, aircraft typically have very long service lives: 30 years for commercial and up to 100 years planned for selected military systems (such as the B-52). Technology evolution and uptake are thus slower than in other forms of transportation. The average age of the air force fleet is approximately 21 years,[36] whereas that of the U.S. commercial fleet is 13 years.[30]

The mission requirements of commercial and military aircraft differ, with the exception of military aircraft used for fuel tankering and transportation (which constitute about half of the military fleet). As a result, specific design trades are made that affect the environmental performance of the systems. In particular, commercial aircraft are designed to maximize range for a given fuel and passenger payload. In doing so, fuel efficiency becomes the most important metric. However, for military aircraft and, in particular, fighter aircraft, maneuverability is a prime design driver in addition to range. Thus, the thrust-to-weight ratio of the aircraft is often as important as fuel efficiency. This difference drives the design of many military and commercial engines in different directions.

Commercial aircraft tend to use high-bypass-ratio engines with large frontal areas, an application suitable only for subsonic flight. Compared to military engines, they are relatively larger in size and weight. Because of the correspondingly low exit velocities, these engines also are relatively quieter than engines with lower mass flows and higher exit velocities. In contrast, many military aircraft missions mandate engines of high thrust to weight for maneuverability, and low frontal area to minimize drag for supersonic flight and to provide better integration with the airframe for low-observability requirements. Thus, the size and weight of the propulsion system are more important and high-specific-thrust (thrust per unit mass flow) engines are typically used. These engines have higher noise because of the higher exit velocities. Military aircraft can also cause sonic boom at high speeds, but such operation is almost always restricted to nonresidential areas. Both types of engines suffer from high NO_x emissions because both employ high temperatures and pressures to increase efficiency and thrust per unit mass flow.

B. Fleet Size and Operational Tempo

Although the size of the fixed-wing military aviation fleet is larger than the commercial fleet, military aircraft are flown at a much slower operational tempo. This has significant implications for noise and fuel use. Figure 5 shows that, over the past decade, the fixed-wing military fleet has dramatically contracted as older systems have been retired and fewer, multi-mission-capable aircraft have been introduced as replacements. Currently the combined air force and navy fleet numbers roughly 9000 aircraft and the commercial fleet numbers approximately 6000 aircraft. Note that in 2000 there were roughly 5500 aircraft in the army fleet; however, only 4% of these were fixed-wing aircraft.[41] In contrast, the commercial fleet has grown, driven by an approximately 4% long-term annual growth in demand for air travel[31] and despite a historical increase in the number of seats per aircraft.[42] Note that subsequent to the events of 11 September 2001, total revenue passenger kilometers (RPKs) fell by 8% and fuel burn by 16%, comparing 2-year averages before and after.[37] In addition, the percentage of the commercial fleet parked increased from 6 to 13%. However, future projections estimate a resumption of the long-term growth trend within the next several years.[31]

Because revenue generation is a primary motivation, utilization of commercial aircraft is much higher than for military aircraft. As shown in Fig. 6, large commercial aircraft are flown on average 4.7 times per day. To arrive at an estimate for military operational tempo, data for flying hours per year[35] were combined with estimates for flying hours per operation for generic aircraft types found in Ref. 43 to estimate operations per year for each type of aircraft. The result

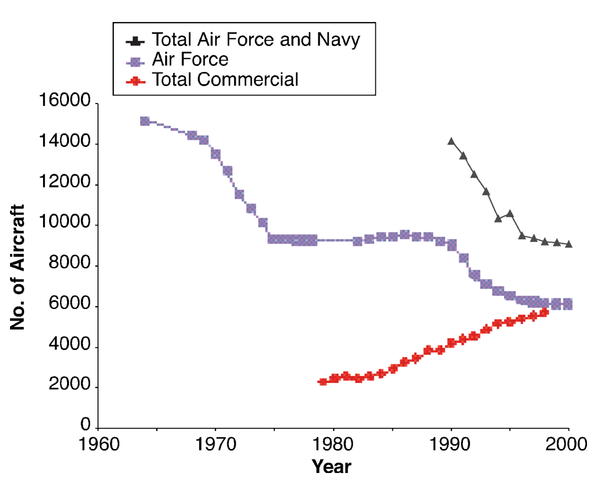

Fig. 5 Military and commercial fleet sizes.[30,32,33,36,38]

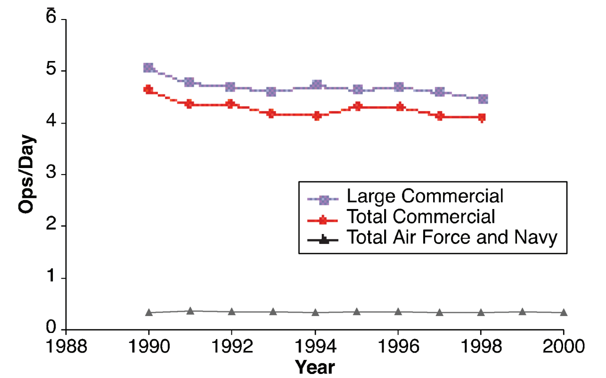

Fig. 6 Average number of daily operations for commercial and military aircraft.[32–37] **Each flight is considered one operation. In other references, each takeoff and landing may be considered separate operations, resulting in two operations per flight.**

indicates a much lower usage of approximately 0.35 times per day, a factor of approximately 13 times less than their commercial counterparts. Historical trends in noise and emissions described in the following sections demonstrate that these differences in operational tempo largely offset differences in technology performance between the military and commercial fleets.

C. Historical Trends in Noise

Military aircraft are, in general, noisier than commercial aircraft on a single-event basis, particularly in certain modes such as afterburning. Figure 7 presents noise levels for military and commercial aircraft presented in terms of EPNL for a single overflight at 1000 ft (~305 m). For reference, an increase of 10 EPNLdB is roughly equivalent to a doubling of annoyance for a single event. It is important to note that the flight profiles used in takeoff and landing are generally different for each type of military and commercial airplane. Using a 1000-ft (~305-m) flyover is a consistent basis for comparison for all of these aircraft but is one step removed from the community noise impact because aircraft-specific operational measures are absent. For commercial aircraft the 1000-ft (~305-m) flyover data are on average 10% higher than certified takeoff noise with a range of 0 to +23%.[28] The correspondence with actual military noise exposures at takeoff averages 5% with a range of −3 to +10% based on comparison with data provided by Shahady.[29] The high noise from tactical military aircraft is a direct result of the high-specific-thrust engines employed by these aircraft. While new production commercial aircraft noise has declined by approximately 15 EPNLdB from 1960 to 1995, there has been an increase in noise from new military fighter aircraft over the same period. There is, however, no evidence of discernable trends for other types of military aircraft.

These historical characteristics are manifest in the fleet average noise levels tracked in Fig. 7, calculated as the logarithmic, operations-weighted average EPNL for the fleet based on the number of operations performed by each aircraft in each year for which data were available. For aircraft with afterburners it is assumed they are used 50% of the time. From the commercial data, a 10- to 15-year lag is apparent between the introduction of new technology and the time for the fleet to reach the equivalent average performance. This is a reflection of the long service lives of commercial aircraft. In Fig. 8, 1000-ft (~305-m) flyover data is shown, organized by the number of operations for each aircraft type in 1990 and 1998 in the air force and navy fleets. Similar information is given for the commercial fleet. By performing a logarithmic sum of the EPNLdB data for each aircraft for each operation as a function of year, it is possible to compare in an approximate way the balance between number of operations and noise intensity in determining the noise impact of the fleet. When such an energy sum is made, data for military and commercial aircraft fall on top of one another as shown in Fig. 8. The calculation again assumes that aircraft with afterburners use them 50% of the time. Although 1000-ft (~305-m) flyover data are only

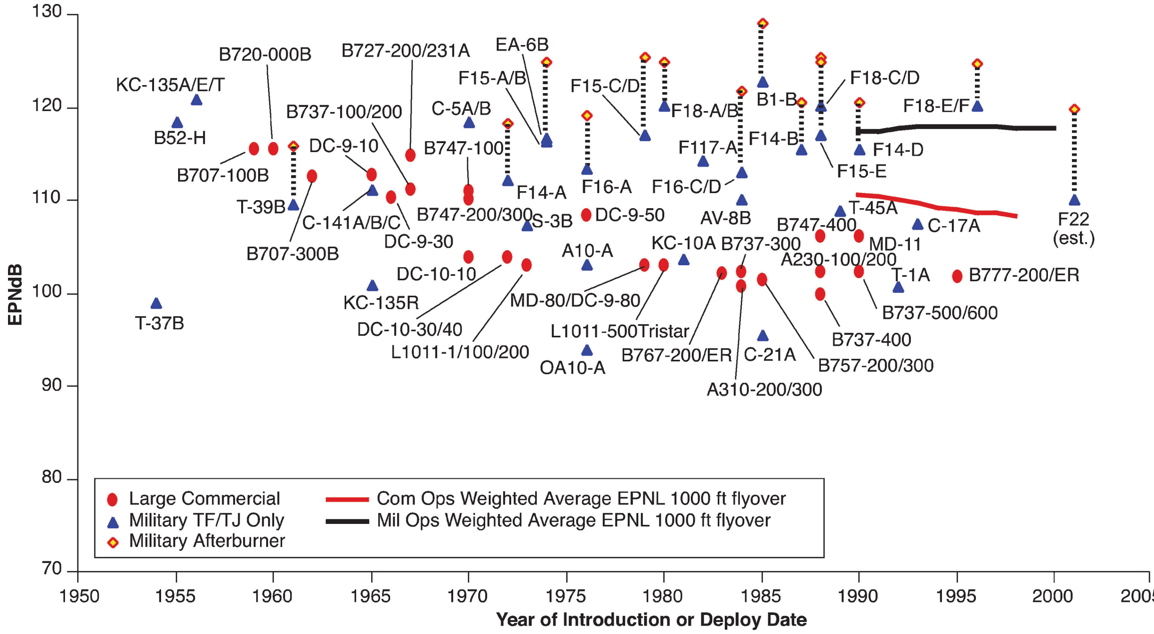

Fig. 7 Effective perceived noise level for military and commercial aircraft, 1000-ft (~305-m) flyover operation.[27,32–37] Operations-weighted fleet averages are shown.

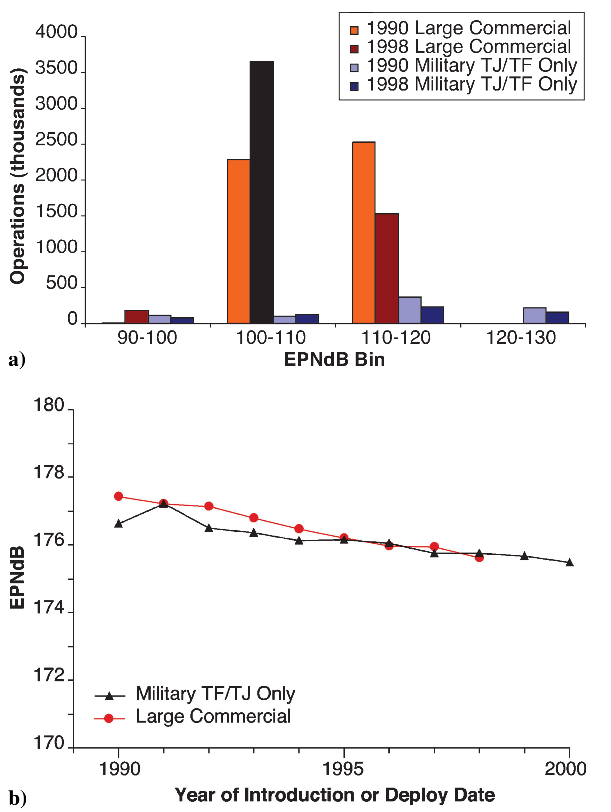

Fig. 8 Effective perceived noise level for military and commercial aircraft, fleet summary, 1000-ft (~305-m) flyover operation.[27,32–37]: a) number of operations is shown categorized by aircraft type and noise level for activity in 1990 and 1998; b) cumulative noise level is shown as an energy sum.

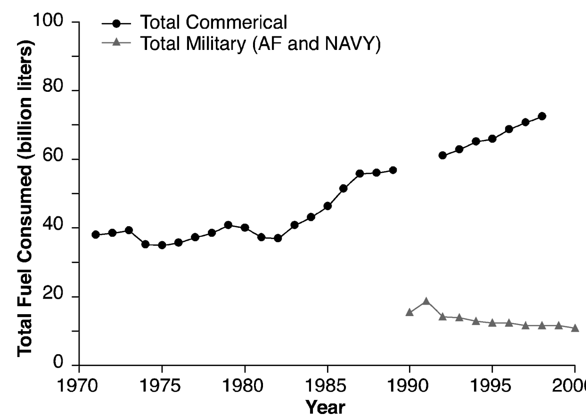

Fig. 9 Fuel use for commercial and military aviation.[32–37]

representative of the single-event noise exposures, Fig. 8 suggests that the high noise levels of military aircraft make up for the small number of operations in comparison to commercial aircraft. This is certainly the case for the specific example shown in Fig. 2.

D. Historical Trends in Emissions

Flying hours data[35] were combined with fuel flow factors[34] to estimate historical trends in fleet fuel use and efficiency for military aircraft. These trends have a direct relationship to CO_2 emissions and when combined with a relevant emission index can be used to develop an understanding of the state of the military fleet with respect to other pollutants such as NO_x. These analyses are pertinent to both local air-quality and climate change impacts.

Approximately 2–3% of the total fossil fuel use in the United States is currently attributed to aviation. This represents about 14% of that used by the transportation sector as a whole.[37,44] As indicated by the total fuel use trends in Fig. 9, the commercial aircraft fleet currently burns approximately seven times the fuel used for military aviation (navy and air force only). Where total fuel use for commercial aircraft has increased, total fuel use for military aircraft has decreased. Although there are more aircraft in the fixed-wing military fleet than in the commercial fleet, military aircraft are flown much less frequently. As a result, air force and navy fuel use for aviation is currently about 0.4% of total U.S. fossil fuel use. The increase in fuel burn for commercial aviation is a reflection of growth outpacing technological improvement. Considering the disproportionate radiative effect of aviation fuel burn relative to ground-based sources discussed in Sec. III.B, these fuel-use levels suggest that U.S. military aviation (excluding the army) may be responsible for approximately 1% of the total U.S. impact on the climate.

Trends in fuel efficiency, presented on a consumption per time basis, are shown for military aircraft in Fig. 10. The evolution of the energy intensity for the U.S. fleet and for individual aircraft by year of introduction based on operating data for the period 1991–1998 is given in Fig. 11. Thirty-one aircraft types are represented covering over 85% of all domestic and U.S. originating or arriving international RPKs performed by the 10 major airlines.[42] Energy intensity is a measure of how much fuel it takes to move one passenger a unit distance (e.g., megajoules of fuel energy per revenue passenger kilometer, MJ/RPK). Because military aircraft are optimized for a broad range of mission requirements, there is no obvious trend toward improved fuel efficiency as in the commercial fleet. However, the importance of fuel efficiency, even for tactical aircraft, is well recognized.[45] Besides reducing operating costs, fuel efficiency provides greater warfighting capability because less fuel must be tankered or transported, thereby enhancing mobility and reducing logistical requirements.

Although reducing energy intensity or fuel consumption tends to reduce overall emissions, there are barriers inherent to air transportation that can act counter to the realized benefit. Reductions in emissions are hindered by the relatively long lifespan and large capital cost of individual aircraft and the inherent lag in the adoption of new technologies throughout the aviation fleet as a result. For commercial aircraft, year-to-year variations in fuel efficiency for each aircraft type, due to different operating conditions such as load factor, flight speed, altitude, and routing controlled by different operators, can be ±30%, as represented by the vertical extent of the data symbols in Fig. 11. A combination of technological and operational improvements has led to a reduction in energy intensity of the entire U.S. fleet of more than 60% between 1971 and 1998, averaging about 3.3% per year. In contrast, total RPKs have grown by 330%, or 5.5% per year over the same period. Growth is anticipated to continue at a rate of ~4% per year after recovery from the downturn following the events of 11 September 2001.[31]

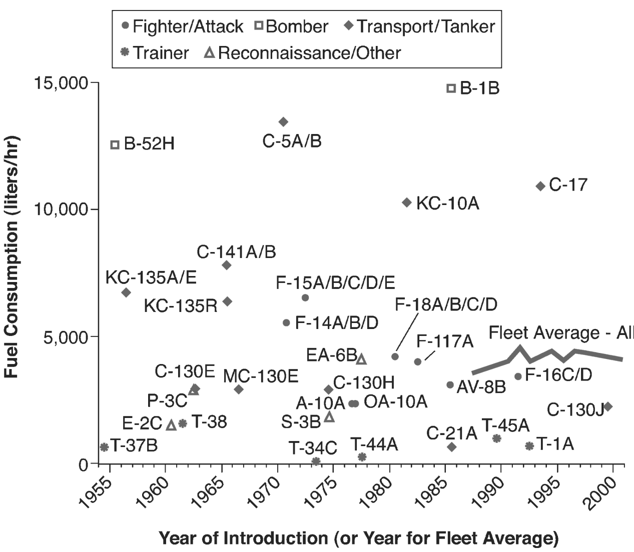

Fig. 10 Historical trends in fuel efficiency for military aircraft.[32–36]

Because of the high temperatures and pressures within both commercial and military aircraft engines, NO_x tends to be the most difficult of the local air-quality pollutants to control. NO_x emissions are thus a useful, conservative benchmark for the impacts of aviation on local air quality. Trends in NO_x emissions for commercial and military aircraft on a per-operation basis are shown in Fig. 12. Consistent with the certification standards, the data represent all emissions that occur below 3000 ft (~915 m) altitude. The large variability among different aircraft is mainly attributable to the wide range of thrust levels and engine pressure ratios across the aircraft in Fig. 12. Note in particular that high values are typically found for large, long-range aircraft. These aircraft also have generally higher fuel efficiencies than other aircraft types as shown in Fig. 11, which highlights the strong tradeoff between fuel efficiency and NO_x. In improving the emissions performance of future aviation systems, such tradeoffs are inevitable.

On average, per operation, there is minimal difference between the NO_x characteristics of commercial and military aircraft. Operations-weighted fleet averages for commercial and military aircraft are almost identical and have been nearly constant over the past 10 years. When the roughly constant fleet-average NO_x emissions per flight are combined with the changes in number of flights per year for military and commercial aircraft, the overall impact of commercial aircraft on local air quality has risen, whereas that for military aviation has declined. These results are depicted in Fig. 13, where

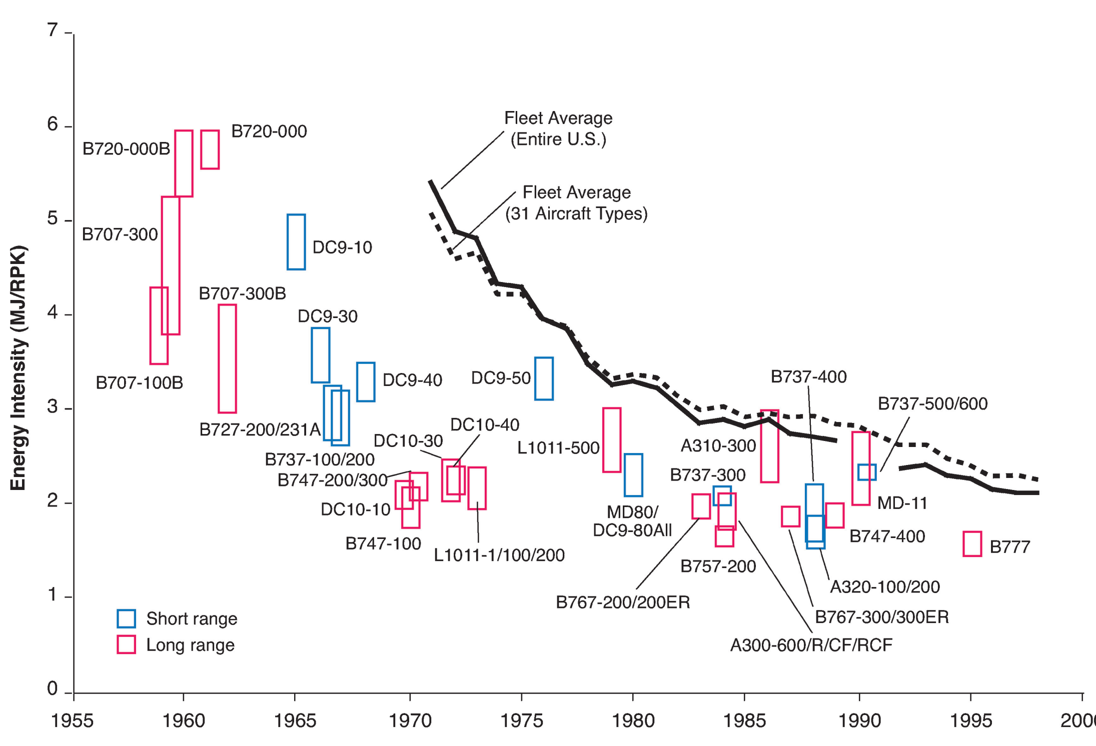

Fig. 11 Historical trends in fuel efficiency for commercial aircraft.[37,42]

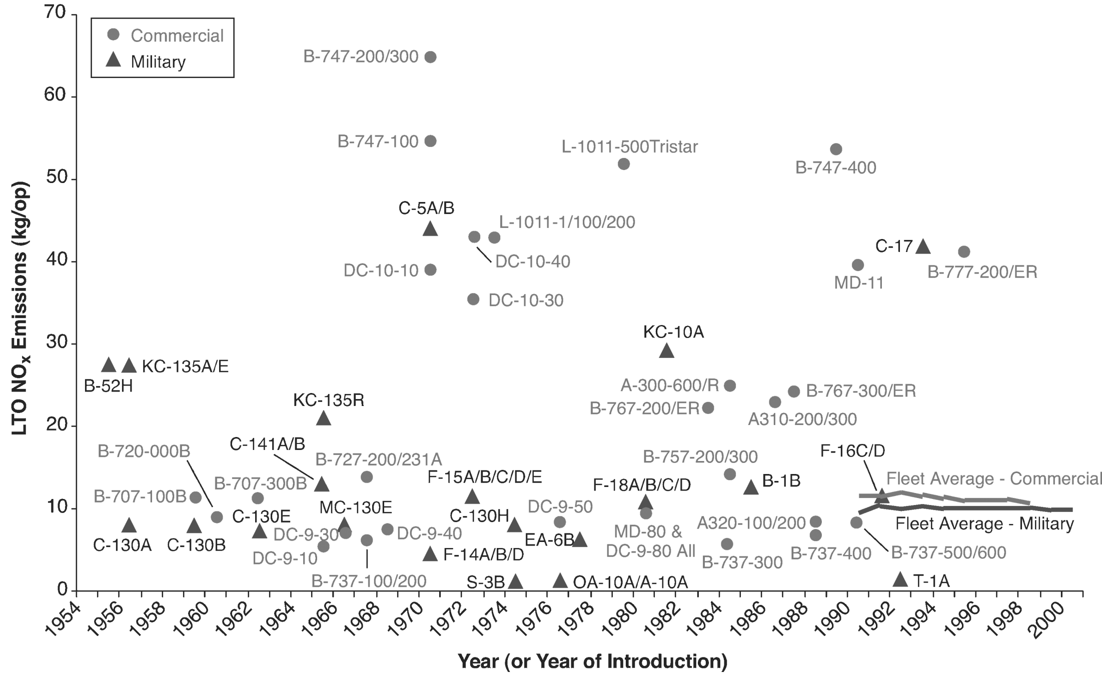

Fig. 12 Landing/takeoff cycle NO_x emissions from military and commercial aircraft (operations-weighted fleet averages are shown).[32–37,48]

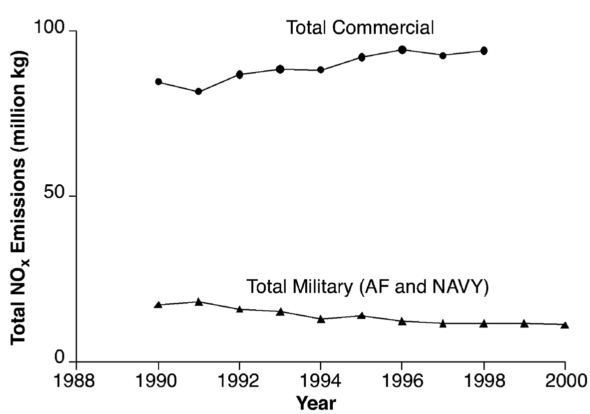

Fig. 13 Total NO_x emissions from the commercial and military fleets.[32–37,48]

it can also be seen that the total NO_x emissions from commercial aircraft are nearly six times those of military aviation. Less than 1% of all U.S. mobile source emissions of NO_x come from commercial, military, and general aviation aircraft.[46–48]

V. Summary

To explain the factors that govern the relationship between military aviation and the environment, this paper has presented a review of the current issues and trends related to noise and emissions impacts. Against a backdrop of increasing public concern about the environment and increasing regulatory stringency, the impact of military aviation on the environment has decreased when averaged nationally. This is a result of roughly constant levels of technology performance coupled with reduced numbers of aircraft and operations and is reflected in terms of fuel burn, total NO_x emissions, and integrated measures of community noise. Nonetheless, environmental issues are increasing in importance in terms of their impact on national security. Encroachment on training and constraints on basing choice directly result from requirements to assess and minimize environmental impact. Trends for commercial aviation have been quite different, with evolutionary improvements in technology coupled with rapid growth in numbers of aircraft and operations. These have led to generally increased environmental impacts from commercial aviation for emissions and decreased impacts for noise over the period considered (1960–2000).

There has been a significant change in public willingness to accept noise from aircraft. Although the number of people living in a contour of constant noisiness in the United States has been reduced by a factor of 15 over the past 30 years, noise complaints and associated constraints on airport expansion and airline operations continue. Against this trend, commercial aircraft are generally getting quieter at a rate estimated to almost balance the increased number of operations in the future. Similarly, military aircraft are producing a roughly constant level of community noise. Notably, the relatively small number of operations by military aircraft does not compensate for the relatively high level of single-event noise, which is at least twice as annoying on average than commercial aircraft. As the demand for environmental amenities such as quiet grows, as areas around bases become increasingly urbanized, and as requirements for range use increase, noise constraints on military aviation are expected to rise.

Trends in NO_x emissions were employed in this discussion as a surrogate for air-quality impacts from military aviation. New military and commercial aircraft tend to have higher NO_x emissions than older aircraft as a byproduct of the higher temperatures and pressures used in modern engines for reduced fuel burn and higher thrust-to-weight ratio. Although the contraction of the military fleet has reduced the total national NO_x emissions, the contraction typically came about through base closures. Therefore, the local air-quality impact around any one base may be expected to increase as new aircraft such as the Joint Strike Fighter are introduced into the fleet. This is a particularly important issue for the military with respect to the conformity requirements of the CAA.

The policy outlook for the impact of climate issues on military aviation is uncertain. Aviation is currently responsible for approximately 2–3% of U.S. fossil fuel use. Roughly 0.4% is attributable to military aviation. However, fuel burn at altitude is estimated to lead to a disproportionate impact on the environment (by roughly a factor of 2). Thus, it can be approximated that 1% of all U.S. anthropogenic forcing of the climate is presently related to military aviation. Whereas commercial aviation is expected to see improvements in fuel burn averaging about 1% per year,[42] similar improvements are not expected for military aviation. This is because of the unique requirements for speed and maneuverability for military aircraft, such that fuel burn is not always the dominant design requirement, and also because of the very slow evolution of the military fleet due to high capital costs. The average age of the military fleet is 21 years vs 13 years for the commercial fleet.

It is critical to establish and monitor trends nationally as part of communicating changes in environmental impact. This should include maintaining estimates of the number of people impacted by military aviation noise and emissions. This review is intended to help launch a consideration of the factors that determine information needs concerning environmental impact, but also to highlight that tools and processes to assess the national security impact of various operational restrictions are not available. This is perhaps the most important challenge for the DoD in achieving an effective balance of national security and environmental impact. Currently, the DoD has little specific quantitative information to assess impacts of environmental restrictions on training and readiness.

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References

[1]U.S. Department of Defense, "FY 2001 Defense Environmental Quality Program Annual Report to Congress," Office of the Deputy Under Secretary of Defense (Installations and Environment), 2001.

[2]U.S. Department of Defense, "Implementation of the Department of Defense Training Range Comprehensive Plan: Insuring Training Ranges Support Training Requirements, Report to the Congress," Office of the Under Secretary of Defense (Personnel and Readiness), Feb. 2004.

[3]U.S. Department of Defense, "Readiness and Range Preservation Initiative," Defense Environmental Network and Information Exchange [online], URL: http://www.denix.osd.mil/denix/Public/Library/Sustain/RRPI/rrpi.html [cited 9 June 2004].

[4]U.S. Air Force, "Final Environmental Impact Statement for Initial F-22 Operational Wing Beddown," Air Combat Command/Environmental Analysis Branch, Langley AFB, VA, Nov. 2001.

[5]Engleman, L., "Draft Airborne Noise Encroachment Action Plan, Pre-Decision Working Paper," Sustainable Ranges Outreach Committee, Department of Defense, U.S. Air Force, Bases and Units Branch, Washington, DC, 2001.

[6]Fallon, W. J., "Statement Before the House Committee on Government Reform on Constraints on Military Training," Department of Defense, Office of the Chief of Naval Operations, Washington, DC, May 2001.

[7]Bowers, T., "Draft Air Quality Action Plan, Pre-Decision Working Paper," Sustainable Ranges Plan, Department of Defense, Office of the Chief of Naval Operations, Washington, DC, 2001.

[8]Fargo, T. B., "United States Pacific Fleet Briefing," U.S. Pacific Fleet, Pearl Harbor, HI, June 2001.

[9]Levin, C., and Warner, J., "Senate and House Complete Conference on National Defense Authorization Bill for Fiscal Year 2002," Press Release, U.S. Senate Committee on Armed Services, Washington, DC, Dec. 2001.

[10]Federal Interagency Committee on Aircraft Noise, "Federal Agency Review of Selected Airport Noise Analysis Issues," Washington, DC, Aug. 1992.

[11]World Health Organization, *Guidelines for Community Noise*, edited by B. Berglund, T. Lindvall, and D. H. Schuela, Cluster of Sustainable Development and Healthy Environment, Department of the Protection of the Human Environment, Occupational and Environmental Health, Geneva, 1999.

[12]National Research Council, "Guidelines for Preparing Environmental Impact Statements on Noise," Rept. of Working Group 69, Assembly of Behavioral and Social Sciences, Committee on Hearing, Bioacoustics, and Biomechanics, Washington, DC, 1977.

[13]Morrison, S. A., Winston, C., and Watson, T., "Fundamental Flaws of Social Regulation: The Case of Airplane Noise," *Journal of Law and Economics*, Vol. XLII, No. II, Oct. 1999, pp. 723–743.

[14]U.S. General Accounting Office, "Aviation and the Environment: Transition to Quieter Aircraft Occurred as Planned, but Concerns About Noise Persist: Report to the Ranking Democratic Member, Committee on Transportation and Infrastructure, House of Representatives," GAO-01-1053, Washington, DC, Sept. 2001.

[15]Downing, M., Schmidt-Bremer, M., Kanzler, J., and Amefia, K., "Noise Study for the Introduction of the F/A-18E/F to the East Coast," Wyle Acoustics Group, Wyle Laboratories, WR 02-08, prepared for the Department of the Navy, Engineering Field Activity Chesapeake, Naval Facilities Engineering Command, Washington, DC, April 2003.

[16]National Research Council, *For Greener Skies: Reducing Environmental Impacts of Aviation*, Committee on Aeronautics Research and Technology for Environmental Compatibility, Aeronautics and Space Engineering Board, National Academy Press, Washington, DC, 2002.

[17]U.S. Navy, "Air Installation Compatible Use Zone (AICUZ) Study for NAS Oceana and NALF Fentress," Naval Air Station Oceana, Virginia Beach, VA, 1999.

[18]Intergovernmental Panel on Climate Change, *Aviation and the Global Atmosphere*, edited by J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken, and M. McFarland, Cambridge University Press, Cambridge, England, U.K., 1999.

[19]U.S. Environmental Protection Agency, "Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft, Final Report," ICF Consulting Group, EPA 420-R-99-013, Engine Programs and Compliance Division, Office of Mobile Sources, Ann Arbor, MI, April 1999.

[20]Intergovernmental Panel on Climate Change, "Climate Change 2001: Synthesis Report," Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, Cambridge, England, U.K., 2002.

[21]Stenzel, J., Trutt, J., and Cunningham, C., "Flying Off Course, Environmental Impacts of America's Airports," National Resources Defense Council, New York, Oct. 1996.

[22]U.K. Royal Commission on Environmental Pollution, "The Environmental Effects of Civil Aircraft in Flight," Special Rept., London, Nov. 2002.

[23]U.S. Environmental Protection Agency, "Procedures for Emission Inventory Preparation, Volume IV: Mobile Sources," EPA 420-R-92-009, Emission Planning and Strategies Division, Office of Mobile Sources, and Technical Support Division, Office of Air Quality Planning and Standards, Washington, DC, 1992.

[24]Environmental Quality Management, and Weston, R. F., "Aircraft Engine and Auxiliary Power Unite Emissions Testing Final Report," prepared for the U.S. Air Force, Inst. for Environmental Safety and Occupational Health Risk Assessment, Brooks Air Force Base, TX, Dec. 1998.

[25]International Civil Aviation Organization, *Engine Exhaust Emissions Data Bank* [online database], URL: http://www.qinetiq.com/home/markets/aviation/aircraft_engine_exhaust_emissions_databank.html [cited 17 July 2002].

[26]U.S. Air Force, "Aircraft Air Pollution Emission Estimation Techniques," Air Force Center for Environmental Excellence, Civil and Environmental Engineering Development Office, Tyndall AFB, FL, Sept. 1978.

[27]U.S. Federal Aviation Administration, Integrated Noise Model, Noise Level Database, Ver. 6.0c, Office of Environment and Energy, Washington, DC, Sept. 2001.

[28]U.S. Federal Aviation Administration, "Noise Levels for U.S. Certificated and Foreign Aircraft," Advisory Circular 36-1G, Office of Energy and Environment, Washington, DC, Aug. 1997.

[29]Shahady, P. A., "Military Aircraft Noise," AIAA Paper 73-1291, Nov. 1973.

[30]Fleet PC Database, Ver. 4.0, BACK Aviation Solutions, New Haven, CT, 2001.

[31]U.S. Federal Aviation Administration, "FAA Aerospace Forecasts Fiscal Years 2004-2015," FAA-APO-04-1, Office of Aviation Policy and Plans, U.S. Dept. of Transportation, March 2004.

[32]U.S. Navy, and Fowler, A., "Actual Analysis Report, Version 1261, Fiscal Years 1990–2000," N78CF, Naval Operations Staff (OPNAV), Washington, DC, 2001.

[33]U.S. Air Force, "The USAF Summary," Directorate of Management Analysis, Comptroller of the Air Force, Feb. 1978.

[34]U.S. Air Force, "Command Unique MDS AVFUEL Factor Summary, FY 2000 AFCAIG Cycle," Assistant Secretary of the Air Force (Financial Management and Comptroller), Washington, DC, 2001.

[35]U.S. Air Force, and O'Neill, D. J., "History of USAF Flying Hours for Planning and Programming" A-41 Rept., Training Division, Directorate of Operations and Training, Office of the Deputy Chief of Staff for Air and Space Operations (AF/XOOT), Washington, DC, 2001.

[36]U.S. Air Force, "United States Air Force Statistical Digest FY2000," Assistant Secretary of the Air Force (Financial Management And Comptroller), Washington, DC, 2001.

[37]U.S. Department of Transportation, *Air Carrier Summary Data (Form 41 and 298C Summary Data)* [online database], Bureau of Transportation Statistics, URL: http://www.transtats.bts.gov [cited 1999].

[38]Bushnell, D. M., "The 1998 AIAA Dryden Lecture: Frontiers of the Responsible Imaginable in (Civilian) Aeronautics," AIAA Paper 98-0001, Jan. 1998.

[39]Gunston, B., *Jane's Aero-Engines*, Jane's Information Group, Alexandria, VA, 1998.

[40]Jane's Information Group, *Jane's All the World's Aircraft 1960–2000*, Samson Low, Martin and Co., New York, 1999.

[41]Hinson, E., "Army Aviation Usage Data," U.S. Army, Army Logistics Support Center, Redstone Arsenal, AL, 2001.

[42]Lee, J. J., Lukachko, S. P., Waitz, I. A., and Schafer, A., "Historical and Future Trends in Aircraft Performance, Cost and Emissions," *Annual Review of Energy and the Environment*, Vol. 26, 2001, pp. 167–200.

[43]Metwally, M., "Jet Aircraft Engine Emissions Database Development: 1992 Military, Charter and Nonscheduled Traffic," NASA CR-4684, Nov. 1995.

[44]Energy Information Administration, *Annual Energy Review*, U.S. Dept. of Energy, Washington, DC, 2001.

[45]Defense Science Board, "More Capable Warfighting Through Reduced Fuel Burden," Task Force on Improving Fuel Efficiency of Weapons Platforms, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, DC, Jan. 2001.

[46]U.S. Environmental Protection Agency, "National Air Quality and Emissions Trends Report, 1999," EPA-454/R-01-004, Office of Air Quality Planning and Standards, Emissions Monitoring and Analysis Division, Air Quality Trends Analysis Group, Research Triangle Park, NC, March 2004.

[47]U.S. General Accounting Office, "Aviation and the Environment: Strategic Framework Needed to Address Challenges Posed by Aircraft Emissions: Report to the Chairman, Subcommittee on Aviation, Committee on Transportation and Infrastructure, House of Representatives," GAO-03-252, Washington, DC, Feb. 2004.

[48]U.S. Federal Aviation Administration, Emissions and Dispersion Modeling System, Emission Factors Database, Version 6.0, Office of Environment and Energy, Washington, DC, 2001.