# MILITARY AVIATION AND THE ENVIRONMENT: HISTORICAL TRENDS AND COMPARISON TO CIVIL AVIATION

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## ABSTRACT

This paper articulates trends in the environmental impact of military aviation between 1960 and 2000. 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. Further, 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, since 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, multi-service operations involving longer range, higher speed weapon systems.

## LIST OF ABBREVIATIONS

| | |
|---|---|
| ATM | air traffic management |
| BRAC | Base Alignment and Closure |
| CAA | Clean Air Act |
| CNS | communication, navigation, and surveillance |
| DNL | day-night noise level |
| DoD | Department of Defense |
| EPA | Environmental Protection Agency |
| EPNL | effective perceived noise level |
| EIS | environmental impact statement |
| FAA | Federal Aviation Administration |
| FCLP | field carrier landing practice |
| IPCC | Intergovernmental Panel on Climate Change |
| NAAQS | National Ambient Air Quality Standard |
| NALF | Naval Air Landing Field |
| NAS | Naval Air Station |
| NCA | Noise Control Act |
| NEPA | National Environmental Policy Act |
| PL | public law |
| PM | particulate matter |
| SIP | state implementation plan |
| UHC | unburned hydrocarbon |
| USC | United States Code |

## 1 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 2 begins by discussing current regulatory measures used to control health and welfare impacts, along with examples of the trade-offs imposed on military operations. Section 3 reviews the pathways through which noise and emissions produced by aviation operations are currently understood to result in environmental change, and identi-

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fies relevant metrics. Section 4 employs these metrics to evaluate the historical evolution of community noise, local air quality, and global climate impacts associated with military aviation. Section 5 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.

## 2 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.[1,2,3] Navy pilot training for aircraft carrier landings in the U.S. 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 $40M to $115M to alleviate these operational impacts.[4]

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 compounds the effect of increasing urbanization. As the DoD pursues more multi-service, 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 last 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 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.[5] While 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.[6,7] A national security exemption in the 1972 Noise Control Act (NCA) (42 USC 4901 to 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.[7] 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 to 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. While 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 (~270 metric tons) of $NO_x$ emissions offsets before the aircraft would be allowed to operate.[8] 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 non-attainment zones, areas that do not meet the primary NAAQS set by the federal government.[9] The military has closed more than a dozen bases in California as part of the Base Realignment and Closure (BRAC) 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, the DoD was authorized to spend up to $4B in public funds for environmental programs (PL107-107).[10] While 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[8] 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, suggest 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. While 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 (PL107-107) would have required a national security impact assessment to be performed in parallel with the EIS. While 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.

## 3 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 overall rated thrust output of the engine. While 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.* kg-$NO_x$ per day). This section reviews the metrics used to judge the magnitude and scope of aviation emissions and noise impacts. Noise is addressed in Section 3.1 and emissions in Section 3.2. Section 4 addresses the underlying technological and operational trends.

### 3.1 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 non-auditory health effects as a direct consequence of aviation noise is not available,[11] but some studies suggest such connections, including hypertension in children.[12] 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 are a variety of well-established procedures and metrics for relating sound measurements to human annoyance. These take account of the non-uniform response of the human ear both in frequency and amplitude, sensitivity to tonal versus 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 one hundred 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.[5] In the absence of

Table 1. Residential response to noise levels described by the DNL measure.[11]

| Effects: | Hearing Loss | Annoyance | | |
|---|---|---|---|---|
| Day-Night Average Sound Level in Decibels | Qualitative Description | % of Population Highly Annoyed | Average Community Reaction | General Community Attitude Towards 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 |

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.[13]

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-hour 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.[11] 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 to 72 dB. Corresponding ranges for suburban and wilderness areas are 48 to 57 dB and 20 to 30 dB, respectively.

It is important to note that while 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 indicates that the number of people living in areas with a DNL of 55 to 65 dB may be 5 to 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 Figure 1 have resulted primarily from two factors: low noise aircraft op

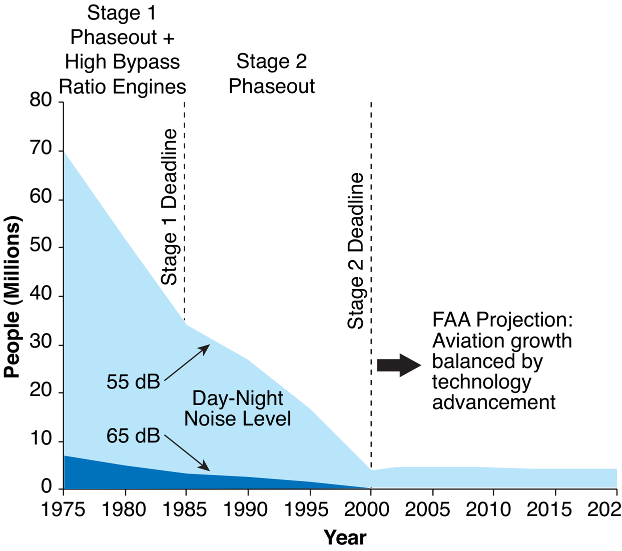


*Figure 1. Estimated number of people exposed to commercial aircraft noise in the U.S.[30] Noise exposure for 65 dB DNL to 1996 estimated from historical FAA sources. Future estimates calculated using the FAA MAGENTA noise model. Exposure to 55 dB DNL is based on scaling from current population distributions around airports.*

erations enabled by advances in aircraft communication, navigation and surveillance, and air traffic management (CNS/ATM) 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 to 2158), is quite significant. While 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 $5B and $10B.[14,15] Over the next 20 years, estimates by the FAA suggest that the number of people affected by commercial aircraft noise in the U.S. 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 Figure 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.[16] 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.[17] A balance between number of operations and the noise level of the related technology explains the difference in exposure area. There are only ~120 take-offs per day at Oceana compared to the average 210 take-offs per day at Norfolk.[18] However, military aircraft can be significantly noisier than their commercial counterparts. These technological and operational trends are further elaborated in Section 4. The large contours around Fentress, built to move FCLP operations from Oceana, are the result of an average of 354 FCLP and 20 take-off operations per day[19] 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.

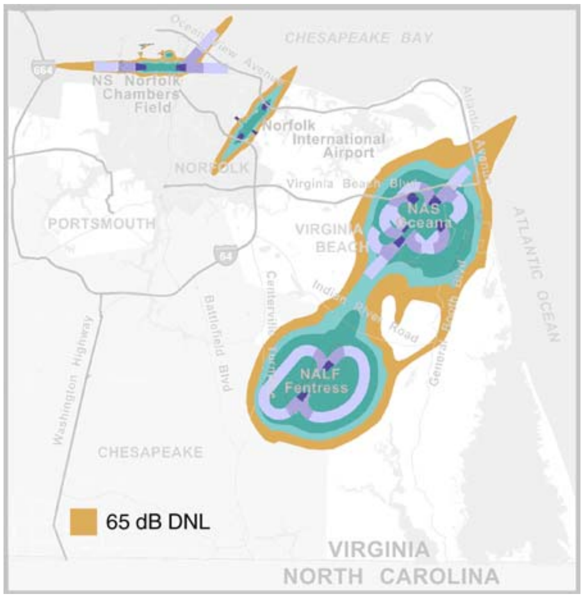


*Figure 2. Noise exposure mappings of DNL contours for NAS Oceana, NALF Fentress, and NS Norfolk Chambers Field with comparison to Norfolk International Airport. Compiled by the DoD Air Installations Compatible Use Zones (AICUZ) program using the NOISEMAP model.[19] Image data provided by J. Ghosen, Ecology and Environment, Inc., Lancaster, NY, 2001.*

### 3.2 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 100's 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.[20,21]

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 (UHC), carbon monoxide (CO), sulfur oxides ($SO_x$), other trace chemical species that include the extended family of nitrogen compounds ($NO_y$), and non-volatile 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 $NO_y$, non-volatile PM, CO, UHC, and $SO_x$ are further related to the manner in which fuel is combusted within the engine and, to some extent, to post-combustion 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.* g-$NO_x$/kg 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 non-volatile 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 (EPA) set limits on ozone, and two size ranges of PM, less than 10 $\mu$m (PM10) and less than 2.5 $\mu$m (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.[20] Climate change is also associated with a broader range of impacts on human and ecosystem health and welfare. [22]

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 Figure 3, which compares the $NO_x$ contributions of Kennedy and LaGuardia airports around New York City to major point sources in the region.[23] In many regions, airports are among the single largest sources with contributions to regional emissions inventories that are typically several percent of the total.[21] For many air quality changes, a direct proportionality between emissions and ambient concentrations can be assumed as a first order estimate of impact.

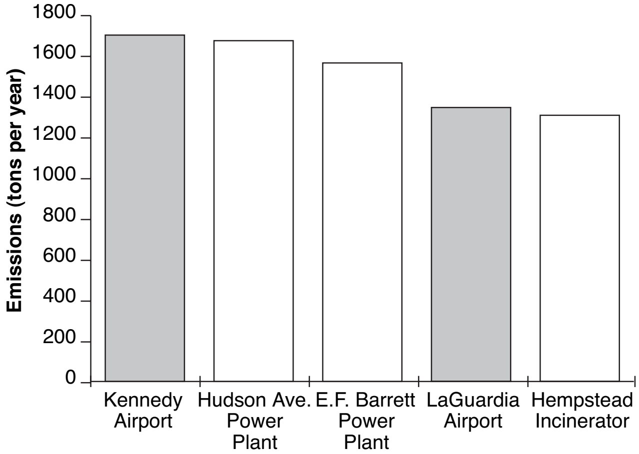


*Figure 3. Ranking of top sources for $NO_x$ emissions for the New York City metropolitan area.[23]*

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 of the atmosphere. Changes in this balance are communicated in terms of radiative forcing, measured in watts per unit of surface area (*e.g.* W/$m^2$). Positive radiative forcing indicates a net warming tendency and is typically determined relative to pre-industrial 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 2 to 4 times more than if the exhaust was $CO_2$ alone. This is largely a result of the effects of $NO_x$ and aviation-induced cloudiness (contrails and cirrus formation), although there is high uncertainty with respect to the latter. In contrast, the overall radiative forcing from the sum of all anthropogenic activities is estimated to be a factor of 1.5 times $CO_2$ alone.[20]

Figure 4 shows recent estimates of the radiative forcing by various aircraft emissions for 1992 and projections for the year 2050 published by the Intergovernmental Panel on Climate Change (IPCC).[20] 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. While broadly consistent with these IPCC projections, subsequent research reviewed by the Royal Commission on Environmental Protection has suggested that the climate impact indicated in Figure 4 is likely to be an underestimate.[24] In particular, while 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 has 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.

## 4 TRENDS IN MILITARY AIRCRAFT ENVIRONMENTAL PERFORMANCE

In light of increasing demand for environmental protection and increasing requirements for range access[8] to

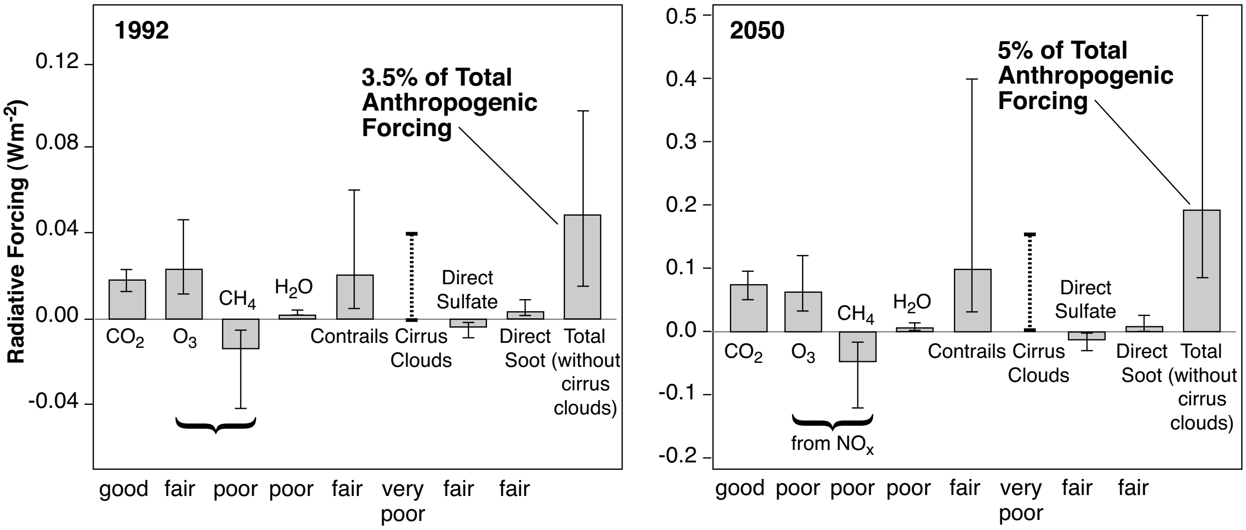


*Figure 4. Aircraft radiative forcing estimated for 1992 (+0.05 $W/m^2$ total) and projected to 2050 (+0.19 $W/m^2$ total).*[20] *Note differences in scale. Notations below graphs indicate the level of scientific understanding for the impact of each exhaust species. The heavier dashed bar for aviation-induced cirrus cloudiness describes the range of estimates, not the uncertainty.*

maintain national security, it is valuable to assess trends in the environmental performance of military aviation systems. This section examines these trends, and in order to highlight the governing factors, our analysis further reflects the evolution of military aviation noise and emissions characteristics against similar characteristics in commercial aviation. 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 4.1 briefly reviews the functional requirements of military and commercial aircraft and their effect on aircraft and engine design, noise, and emissions. Section 4.2 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 Sections 4.3 and 4.4, 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,[25-31] fleet and operational statistics,[32-39] and descriptions of aircraft and engine parameters. [40-42] The analysis considers only fixed-wing aircraft.

### 4.1 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 ($100M for a commercial aircraft, and as high as $1B for some military aircraft). Further, 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 is thus slower than in other forms of transportation. The average age of the Air Force fleet is approximately 21 years[38] whereas that of the U.S. commercial fleet is 13 years. [32]

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 corre

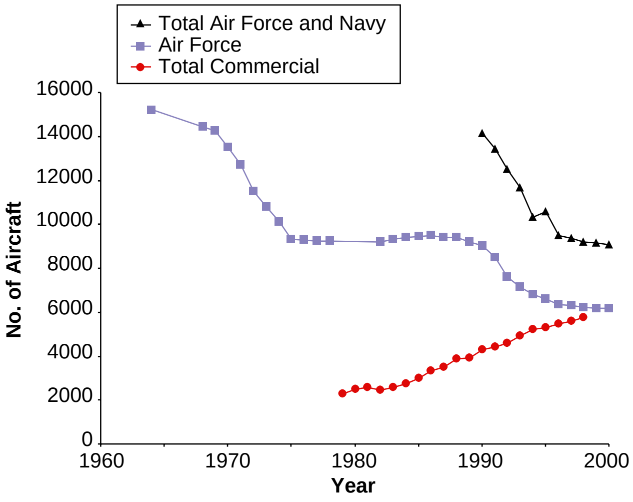


*Figure 5. Military and commercial fleet sizes.*[32,34,35,38,40]

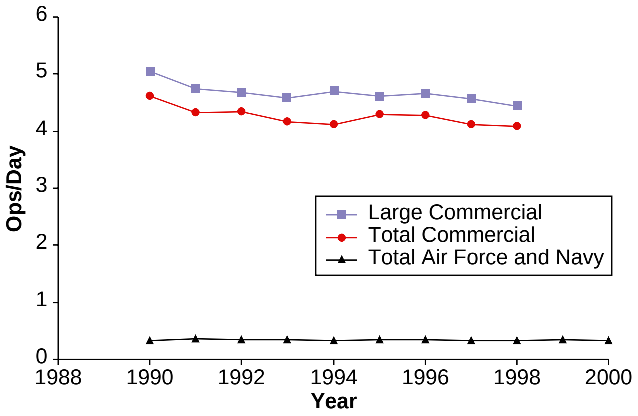


*Figure 6. Average number of daily operations for commercial and military aircraft.*[34-39] *Each flight is considered one operation. In other references, each take-off and landing may be considered as separate operations, resulting in two operations per flight.*

spondingly 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 non-residential areas. Both types of engines suffer from high $NO_x$ emissions since both employ high temperatures and pressures to increase efficiency and thrust per unit mass flow.

### 4.2 Fleet Size and Operational Tempo

While 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 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.[43] In contrast, the commercial fleet has grown, driven by an approximately 4% long-term annual growth in demand for air travel [33] and despite an historical increase in the number of seats per aircraft.[46] Note that subsequent to the events of September 11, 2001, total revenue passenger kilometers (RPK) fell by 8% and fuel burn by 16%, comparing 2-year averages before and after.[39] 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.[33]

As revenue generation is a primary motivation, utilization of commercial aircraft is much higher than for military aircraft. As shown in Figure 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 [37] were combined with estimates for flying hours per operation for generic aircraft types found in Metwally [44] to estimate operations per year for each type of aircraft. The result indicates a much lower usage of approximately 0.35 times per day, a factor of approximately 13 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.

### 4.3 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 EPNdB is roughly equivalent to a doubling of annoyance for a single event. It is important to note that the flight profiles used in take-off 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 since aircraft-specific operational measures are absent. For commercial aircraft the 1000 ft (~305 m) flyover data are on average 10% higher than certified take-off noise with a range of 0% to +23%.[30] The correspondence with actual military noise exposures at take-off averages 5% with a

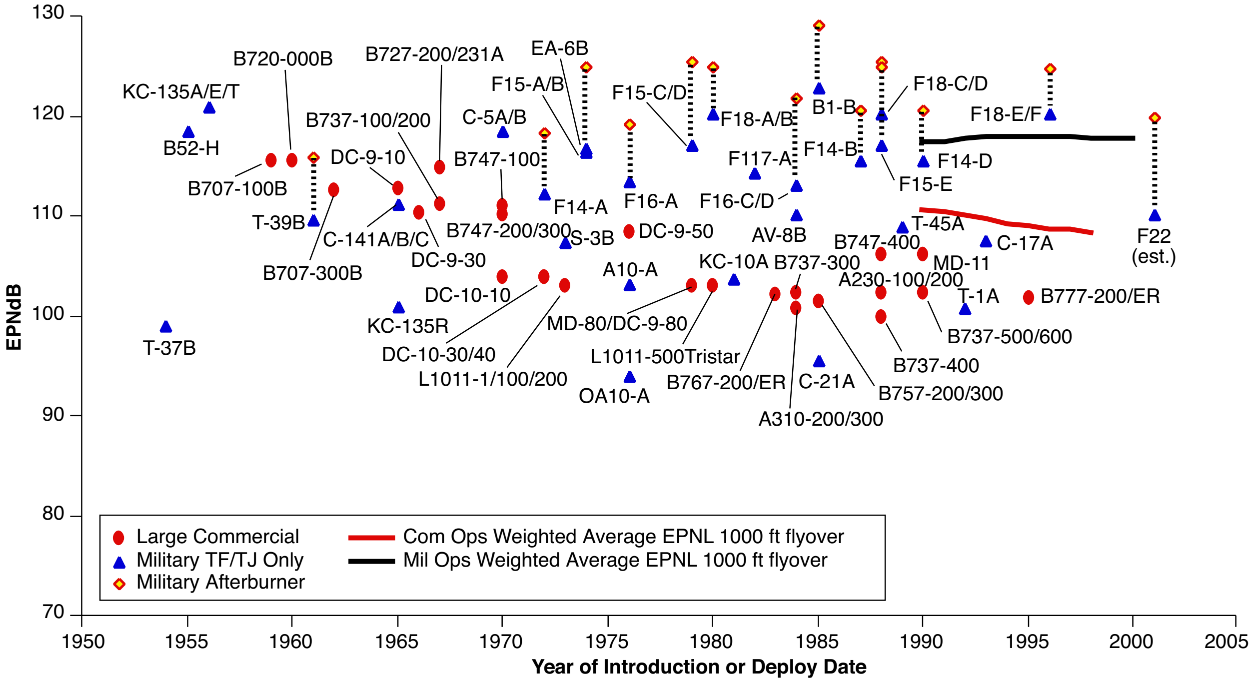


*Figure 7. Effective perceived noise level for military and commercial aircraft, 1000 ft (~305 m) flyover operation.[29,34-39] Operations-weighted fleet averages are shown.*

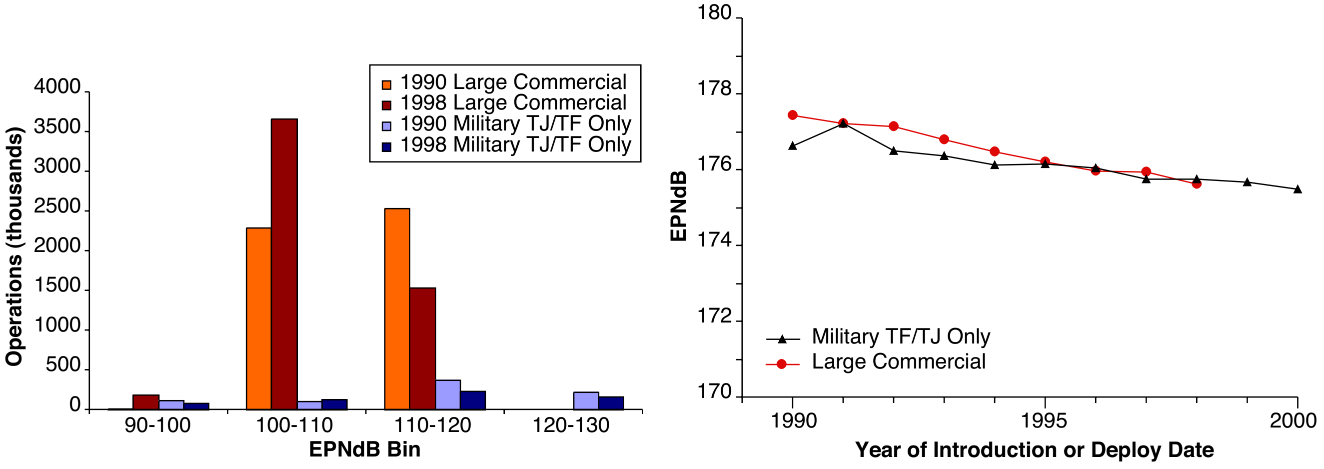
range of –3% to +10% based on comparison with data provided in Shahady.[31] The high noise from tactical military aircraft is a direct result of the high specific thrust engines employed by these aircraft. Where new production commercial aircraft noise has declined by approximately 15 EPNdB from 1960 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 Figure 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 was 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 Figure 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 EPNdB 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 Figure 8. The calculation again assumes aircraft with afterburners use them 50% of the time. Although 1000 ft (~305 m) flyover data is only representative of the single event noise exposures, Figure 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 Figure 2.

## 4.4 Historical Trends in Emissions

Flying hours data [32,37] were combined with fuel flow factors [36] 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.[39,45] As indicated by the total fuel use trends in Figure 9, the commercial aircraft fleet currently burns approximately 7 times the fuel used for military aviation (Navy and Air Force only). Where total fuel use for commercial aircraft has increased, for military aircraft total fuel use 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



**(a)** **(b)**

*Figure 8. Effective perceived noise level for military and commercial aircraft, fleet summary, 1000 ft (~305 m) flyover operation.*[29,34-39] *In (a), the number of operations is shown, categorized by aircraft type and noise level for activity in 1990 and 1998. In (b), the cumulative noise level is shown as an energy sum.*

disproportionate radiative effect of aviation fuel burn relative to ground-based sources discussed in Section 3.2, 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 Figure 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 Figure 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.[46] Energy intensity is a measure of how much fuel it takes to move one passenger a unit distance (*e.g.* mega-Joules 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 towards improved fuel efficiency as in the commercial fleet. However, the importance of fuel efficiency, even for tactical aircraft, is well recognized.[47] Besides reducing operating costs, fuel efficiency provides greater warfighting capability since less fuel must be tankered or transported, thereby enhancing mobility and reducing logistical requirements.

While 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 effi

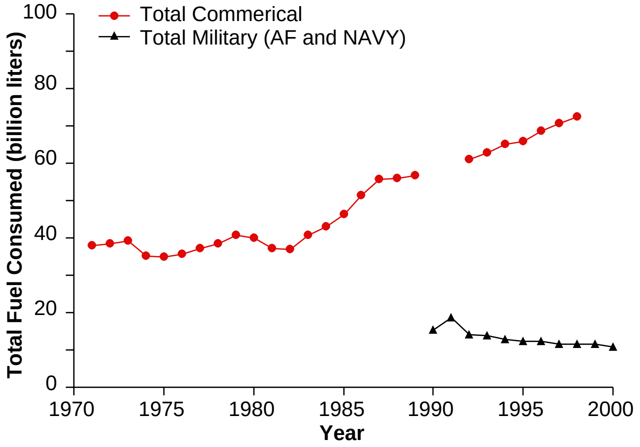


*Figure 9. Fuel use for commercial and military aviation.*[34-39]

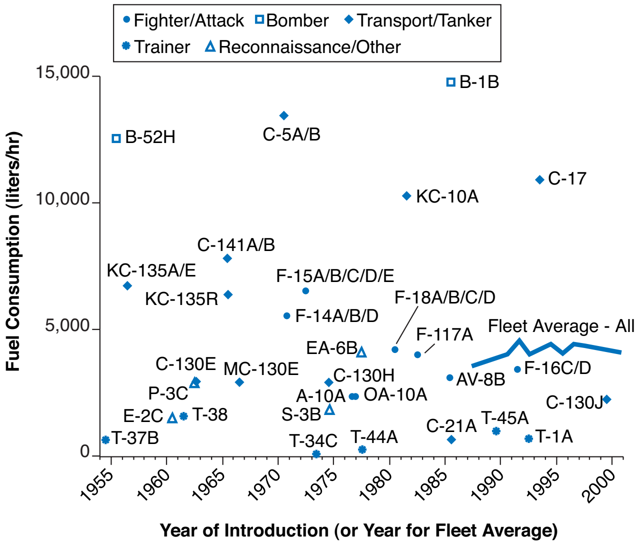


*Figure 10. Historical trends in fuel efficiency for military aircraft.*[34-38]

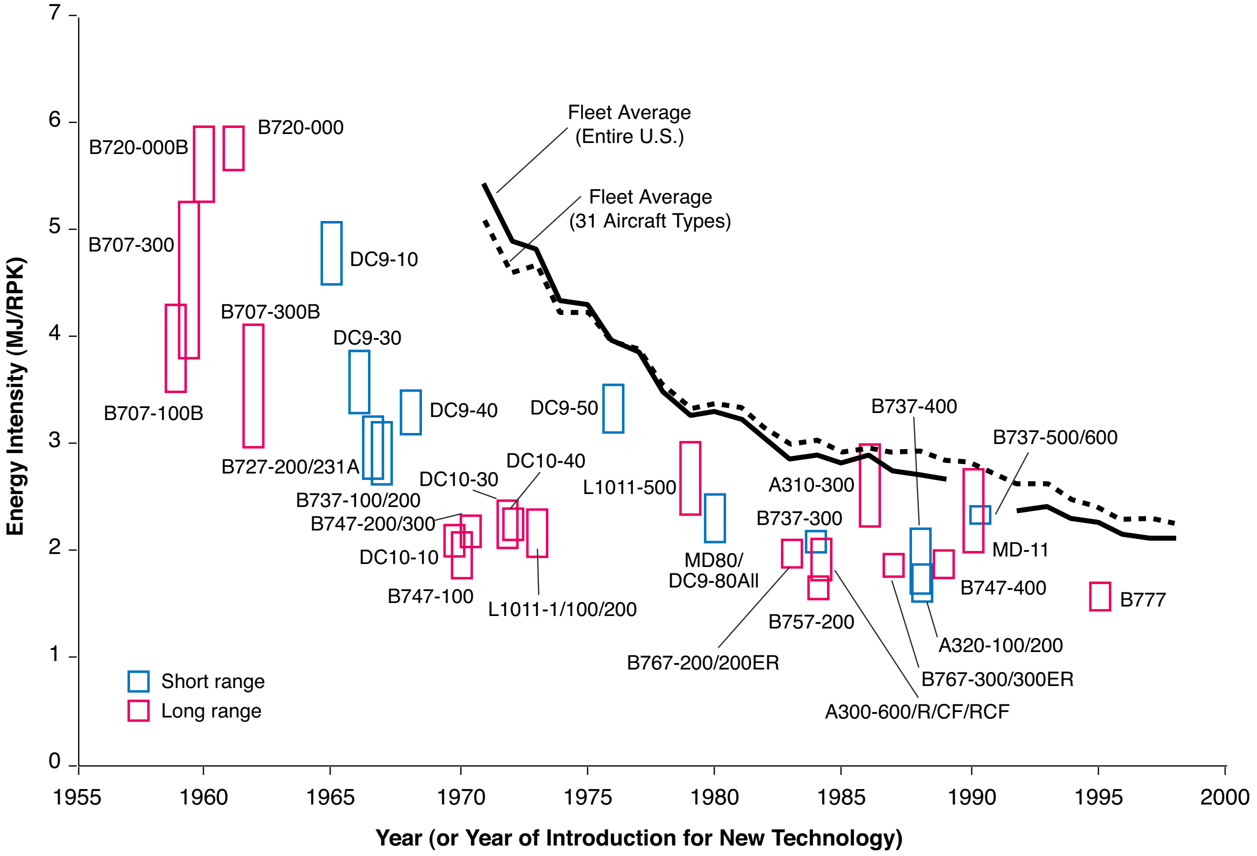


*Figure 11. Historical trends in fuel efficiency for commercial aircraft.*[39,46]

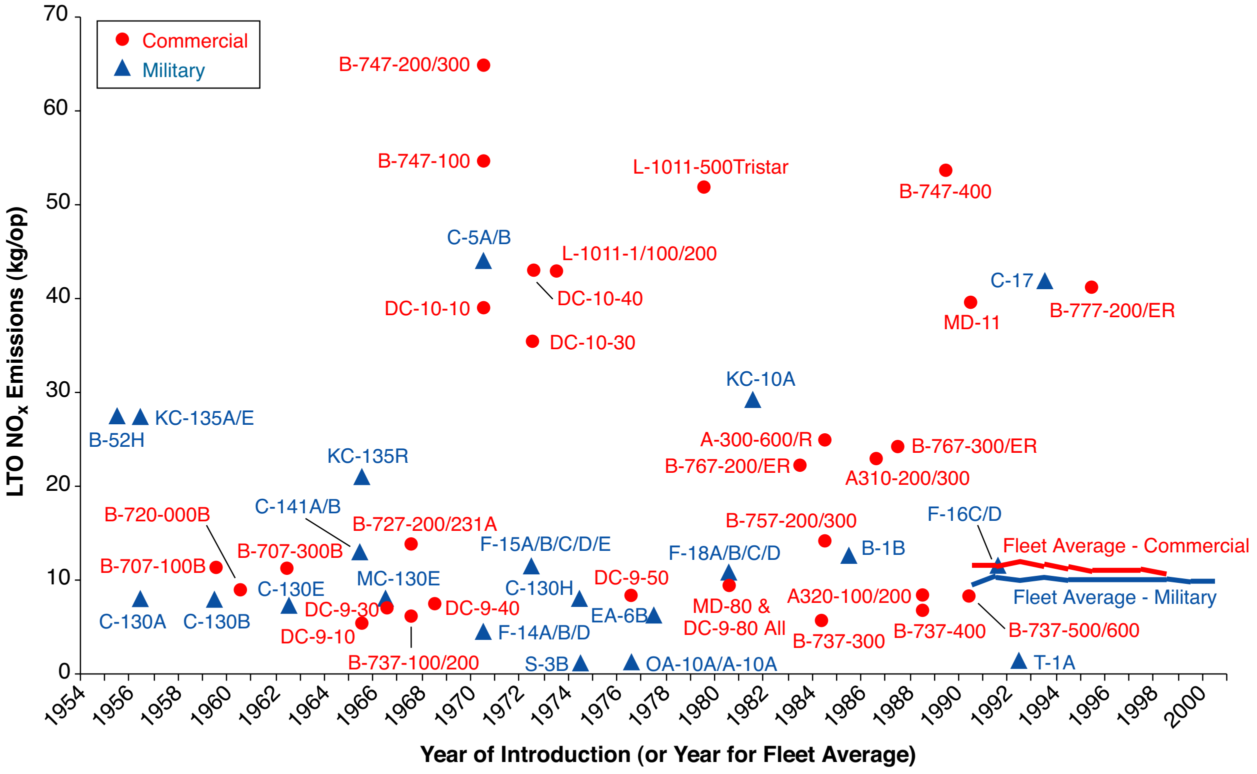


*Figure 12. Landing / take-off cycle $NO_x$ emissions from military and commercial aircraft. Operations-weighted fleet averages are shown.*[34-39,50]

ciency 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 Figure 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 RPK has grown by 330%, or 5.5% per year over the same period. Growth is anticipated to continue at a rate ~4% per year after recovery from the downturn following the events of September 11, 2001.[33]

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 Figure 12. Consistent with the certification standards, the data represent all emissions that occur below 3000 ft (~915 m) altitude. The large variability between different aircraft is mainly attributable to the wide range of thrust levels and engine pressure ratios across the aircraft in Figure 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 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. While the number of people living in a contour of constant noisiness in the U.S. has been reduced by a factor of 15 over the last 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 dein Figure 11, highlighting the strong trade-off between fuel efficiency and NO$_x$. In improving the emissions performance of future aviation systems, such trade-offs 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 last ten 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 Figure 13 where it can also be seen that the total NO$_x$ emissions from commercial aircraft are nearly 6 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.[48,49]

## 5 CONCLUSIONS AND RECOMMENDATIONS

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 mand 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. While the contraction of the military fleet has

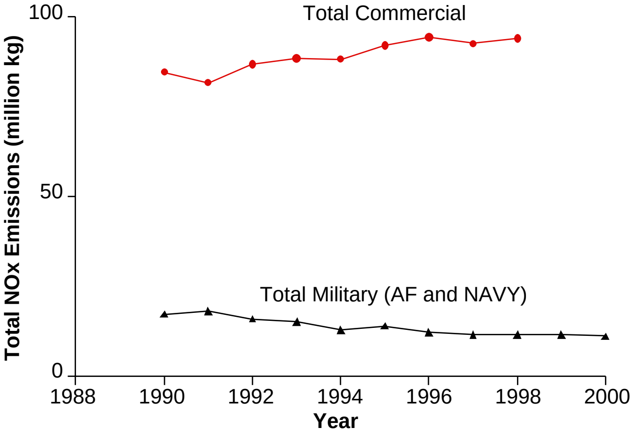


*Figure 13. Total NO$_x$ emissions from the commercial and military fleets.* [34-39,50]

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 two). 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,[46] 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 versus 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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