Federal Aviation Administration

Aviation Emissions, Impacts & Mitigation: A Primer

Office of Environment and Energy

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Introduction

Transportation is an essential contributor to the health and well-being of the nation's economy. Within the transportation sector, commercial aviation has evolved into the fastest, safest, and most far-reaching transportation mode in little more than a century. The world economy benefits greatly from the ability to move people and products all over the globe - quickly and safely. The statistics are impressive. Today, over 3 billion people, nearly half the global population, use the world's airlines.[1] The air transport industry provides 56 million direct, indirect, and induced jobs worldwide, which is double the number of jobs only eight years ago. While aircraft carry only 0.5% of world trade shipments, that represents about 35% of the value of all world trade.[2] This productivity is achieved consuming just 2.2% of world energy.[3]

Aviation contributes to quality of life – allowing us to visit friends and relatives, to travel, to experience new places, to shrink the world. Aviation must develop if it is to continue to meet the needs of a growing economy and an expanding population. At the same time, aviation must be environmentally sustainable, operating harmoniously within the constraints imposed by the need for clean air and water, limited noise impacts, and a livable climate.

The Federal Aviation Administration (FAA) is working with other stakeholders to transform the aviation system to address the challenges and opportunities of the future. In July 2012, it published the "Aviation Environmental and Energy Policy Statement"[4] which identifies and reaffirms FAA's commitment to *environmental protection that allows sustained aviation growth.* The Policy Statement lists the guiding principles of: 1) limiting and reducing future aviation environmental impacts to levels that protect public health and welfare and 2) ensuring energy availability and sustainability.

FAA's Next Generation Air Transportation System (NextGen) will establish the programs, systems, and policies needed for safer, responsive, and more efficient air transport. The FAA's Office of Environment and Energy (AEE) is working to develop new technologies, operations, systems, and fuels to ensure aviation can meet the goals of NextGen while minimizing aviation's impact on the environment. AEE has established a strategic framework to guide research programs for mitigating the environmental impacts of aviation. The framework calls for working with the Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), and other federal agencies as well as industry stakeholders and academia to ensure aviation emissions do not pose health concerns for U.S. citizens or degrade the global climate.

Aviation affects the environment in many ways: people living near airports are exposed to noise from aircraft; streams, rivers, and wetlands may be exposed to pollutants discharged in storm water runoff from airports; and aircraft engines emit pollutants to the atmosphere. This primer describes the emissions associated with commercial aviation and the health and welfare impacts that can result from those aviation emissions that degrade not only air quality but also the broader climate. Noise[5] and water quality[6] considerations are not included in this report but are addressed in other FAA materials.

Aviation Emissions

Aircraft, cars, trucks, and other vehicles operating at the airport create emissions as a result of the combustion of fuel as summarized in Table 1. Aircraft engines produce carbon dioxide (CO_2), which comprises about 70% of the exhaust, and water vapor (H_2O), which comprises about 30%. Less than 1% of the exhaust is composed of pollutants like nitrogen oxides (NO_x), oxides of sulfur (SO_x), carbon monoxide (CO), partially combusted or unburned hydrocarbons (HC), particulate matter (PM), and other trace compounds.

Generally, about 10 percent of aircraft pollutant emissions[7] are emitted close to the surface of the earth (less than 3000 feet above ground level). The remaining 90 percent of aircraft emissions are emitted at altitudes above 3000 feet. The pollutants CO and HCs are exceptions to this rule as they are produced when aircraft engines are operating at their lowest combustion efficiency (while wheels are on the ground), which makes their split about 30 percent below 3000 feet, and 70 percent above 3000 feet.[8]

Aircraft are not the only source of aviation emissions. Airport access and ground support vehicles typically burn fossil fuels and produce similar emissions. This includes traffic to and from the airport, shuttle buses and vans serving passengers, and ground support equipment (GSE) that services aircraft. Other common emissions sources at the airport include auxiliary power units (APU) providing electricity and air conditioning to aircraft parked at airport terminal gates, stationary airport power sources, and construction equipment operating on the airport.

Emission Formation and Transformation.

Many of the pollutants that form in the combustion process transform when they are emitted to the atmosphere. Aircraft pollutants generally transform in three different zones: 1) immediately after exiting the combustor within the engine, 2) downstream from the engine in the hot exhaust plume, and 3) after emissions have cooled and mixed with the ambient atmosphere. At the aircraft engine exit, hot combustion gases mix with ambient air to quickly cool the gas stream. Some gases, like heavy hydrocarbons, can condense under these conditions to form aerosol particles. In the exhaust plume, as emissions continue to cool, some molecules undergo chemical reactions producing other molecules that can also condense into particles. Small particles in the plume collide and form larger particles, although still microscopic in size. The resulting PM in the plume can be solid or liquid and include carbon in the form of soot, inorganic salts (like ammonium nitrate and ammonium sulfate), and heavy hydrocarbons that condense into aerosol particles.

Likewise, gaseous and particle emissions from cars, trucks, and ground vehicles that have exhaust pipes, catalytic converters or particle traps, and mufflers, transform in the exhaust plume after mixing with the ambient atmosphere. Most of the aviation-related PM that reaches airport communities are particle emissions that are released during ground operations and landing and takeoff. Local communities are less affected by PM emissions from cruise operations.

Table 1: Aviation Emissions

Emission	Description	Emission Sources	Impacts
CO_2	Carbon dioxide is the product of complete combustion of hydrocarbon fuels like gasoline, jet fuel, and diesel. Carbon in fuel combines with oxygen in the air to produce CO_2	• Aircraft • APU • GSE • Vehicles • Stationary power plants • Construction equipment	• Climate change
H_2O	Water vapor is the other product of complete combustion as hydrogen in the fuel combines with oxygen in the air to produce H_2O. This is the source of water in condensation trails (contrails).	• Aircraft • APU • GSE • Vehicles • Stationary power plants • Construction equipment	• Climate change
NO_x	Nitrogen oxides are produced when air passes through high temperature/high pressure combustion and nitrogen and oxygen present in the air combine to form NO_x. Contributes to ozone and secondary particulate matter formation.	• Aircraft • APU • GSE • Vehicles • Stationary power plants • Construction equipment	• Air quality • Climate change
HC	Hydrocarbons are emitted due to incomplete fuel combustion. They are often referred to as unburned hydrocarbons (UHC) or volatile organic compounds (VOCs) [VOC excludes some low reactivity compounds found in measures of HC[9]] Some of the compounds in the HC emissions are toxic and hazardous air pollutants (HAPs). Contributes to ozone formation.	• Aircraft • APU • GSE • Vehicles • Stationary power plants • Construction equipment	• Air quality
CH_4	Methane is the most basic hydrocarbon. Commercial aircraft are net consumers of methane during cruise and are not listed in the emissions source column. The net impact of methane from airport sources is highly dependent on local circumstances.	• APU • GSE • Vehicles • Stationary power plants • Construction equipment	• Air quality
CO	Carbon monoxide is formed due to the incomplete combustion of the carbon in the fuel. Contributes to ozone formation.	• Aircraft • GSE • Vehicles • Construction equipment	• Air quality

SO_x	Sulfur oxides are produced when small quantities of sulfur, present in essentially all petroleum fuels, combine with oxygen from the air during combustion. Contributes to secondary particulate matter formation.	• Aircraft • APU • GSE • Construction equipment	• Air quality • Climate change
Particulate Matter (non-volatile)	Small particles of soot (a.k.a. black carbon) that form as a result of incomplete combustion and aerosols from condensed gases, which are small enough to be inhaled, are referred to as particulate matter. Discussed in detail in Health and Environmental Effects Section.	• Aircraft • APU • GSE • Vehicles • Stationary power plants • Construction equipment	• Air quality • Climate change

As aircraft and vehicle emissions mix with the ambient atmosphere, further chemical reactions occur. These reactions involve both molecules emitted from the aircraft and vehicle engines as well as molecules already in the air. For example, ozone is formed by the reaction of VOCs and NO_x in the presence of heat and sunlight. Also, complex chemical reactions and/or particle nucleation processes can produce new particles or add to pre-existing particles. The subsequent particles that are formed can be an order of magnitude greater than primary particles[10]. These particles are estimated to represent more than 95% of total particle formation[11] and expose people over a much broader geographic range. Other examples are the conversion of nitrogen dioxide (NO_2) from the plume to nitric acid (HNO_3) vapor that interacts with ammonia in the atmosphere and forms ammonium nitrate (NH_4NO_3) particles and oxidation reactions involving gaseous hydrocarbons from the plume, yielding condensable organic compounds that form organic aerosol particles. Ammonia, stemming primarily from agricultural activities, is the main alkaline component in the atmosphere and is highly reactive in forming aerosols.

Aviation Climate Change Emissions Compared to Other Transportation Modes.

Only some, but not all, greenhouse gas emissions, such as CO_2, are directly related to fuel use, and most transportation modes use similar fuels. For that reason, energy intensity – the amount of energy consumed to transport one passenger one mile – is a useful metric for comparing greenhouse gas emissions among different transportation modes. Rail, at 2,750 BTU/passenger miles, has the lowest energy use per passenger mile among primary transport modes and transit buses the highest at 4,364 BTU/passenger miles.[12] Aviation and automobiles have efficiencies between those two.

Aviation stands out among transportation modes, however, in terms of improving fuel efficiency over the past decade. As shown in Figure 1: Comparison of Vehicle Fuel Efficiency, in 2004, automobiles and airlines operating in the U.S. had very similar energy intensities, with automobiles at 3,496 BTU/passenger mile versus airlines at 3,505 BTU/passenger mile. Between 2004 and 2012, auto energy intensity fell to

3,193 BTU/passenger mile, for an 8.8% improvement. For the same period, aviation energy intensity fell to 2,654 BTU/passenger mile, a 24.3% improvement and is now significantly lower than automobiles.

These trends were confirmed in a recent study. Aviation is now approaching rail as the most energy efficient transportation mode based on energy intensity per passenger mile.

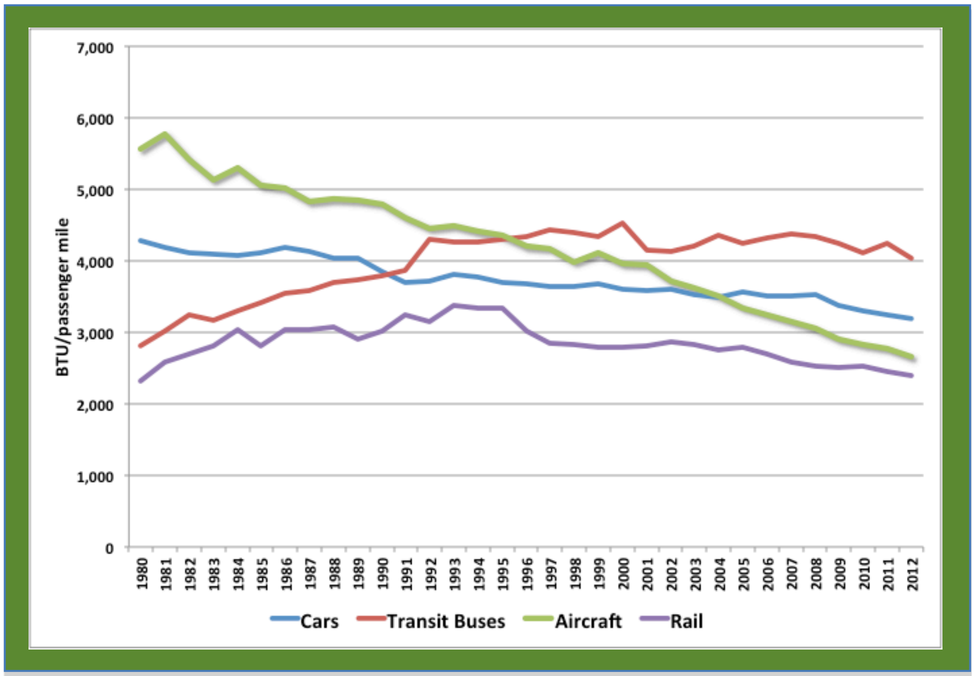

Figure 1: Comparison of Vehicle Fuel Efficiency
U.S. data for different transportation modes from various government agency data resources as compiled by the Oak Ridge National Laboratory Center for Transportation Analysis[13]

Aviation Emissions Compared to Other Transportation Modes*.*

Aviation has grown faster than other modes of transportation and is expected to outpace them in the future. Despite this growth, aviation's contribution to emissions inventories compared to other transportation sources has remained modest, particularly compared to on-road sources. Although the *rate of growth* in the mass of aviation NO_x emissions has exceeded on-road (i.e., cars and trucks) NO_x emissions growth, the *quantity of emissions* of other transport modes still far exceeds those from aviation as illustrated in Figure 2: Transportation Emissions. In part this is not surprising as most of an aircraft's operations take place at altitude where emissions have an uncertain and indirect effect on ground-level air quality spread out over a wide geographic area. This is in contrast to cars and trucks that primarily operate within a single air quality region and always at ground level.

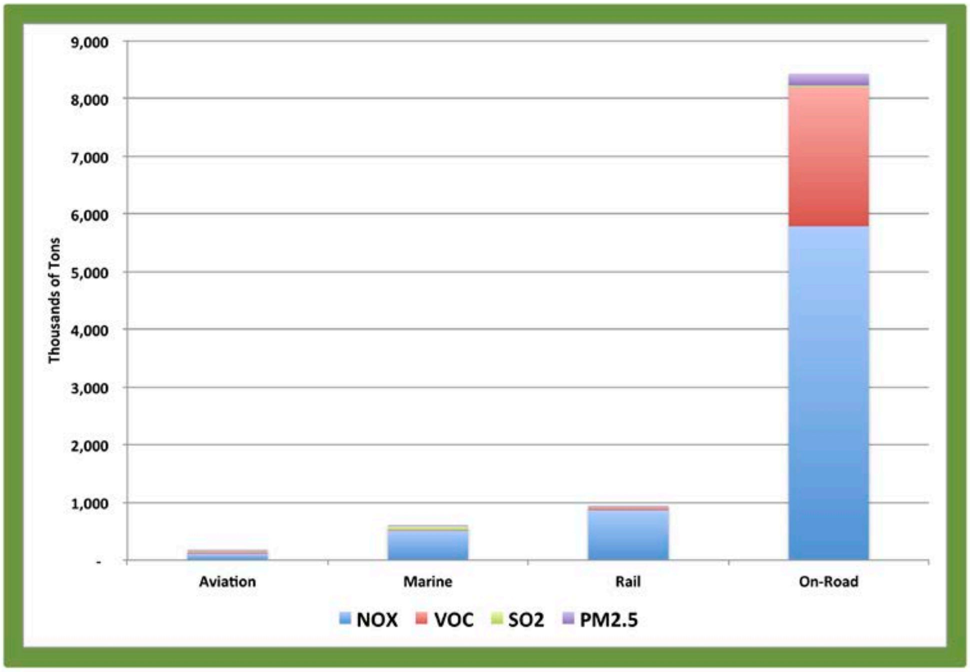

Figure 2: U.S. Transportation Emissions
2011 total U.S. pollutant emissions from primary transportation modes[14]

In the future, NO_x emissions from on-road vehicles will fall in response to the most recent environmental regulations, which call for nearly doubling corporate average fuel economy from 29 miles per gallon currently to 54.5 miles per gallon by 2025.[15] Nonetheless, pressure on aviation sources will likely remain as many states and localities will face the challenges of meeting new ozone and particulate matter standards at the same time non-aviation source reductions become more difficult and costly.

Aviation Emissions Compared to Other Sources of Emissions.

There is an understandable interest in comparing the total mass of emissions coming from an airport to those of a power plant or petroleum refinery in the same region.[16] Airports, however, are quite different from most other emissions sources. Like cities, they comprise a variety of different emission sources. Aircraft arrive at the airport, stay for a short period and depart, with a different aircraft taking off or landing every few minutes. Passenger cars, shuttle buses, and taxis calling on the airport do not operate there exclusively, also serving homes and retail, commercial, and governmental establishments. Power boilers and chillers at the airport are independently permitted, as is similar equipment at other locations. For these reasons it is difficult to compare the composite of sources that make up an airport to another emission source like an industrial facility or power plant. Table 2 provides a list of the contributions of aircraft emissions to major metropolitan statistical areas inventories with the highest contribution of aircraft emissions to total inventory.

Table 2: Aircraft Emissions Contribution to Metropolitan Area Emissions Inventories

Metropolitan Area	NO_x%	VOC%	$PM_{2.5}$%
Washington, DC	1.22	0.57	0.21
Philadelphia	0.64	0.35	0.20
New York	1.40	0.42	0.41
Denver	1.42	0.54	0.31
San Francisco	1.57	0.63	0.29
Dallas	1.76	0.58	0.23
Minneapolis	1.07	0.59	0.39
Chicago	1.27	0.49	0.36

The contribution of aircraft LTO (Landing-Take Off) operations at commercial service airports to emissions inventories has been calculated at an average of 0.37% for SO_x (with a range of 0.002% to 6.91%) and 0.44% for CO (ranging from 0.06% to 4.36%).[17]

Effects of Economic Growth on Emissions.

The level of aviation activity reflects the overall demand for worldwide travel and trade. Demand for travel services, both passenger travel and freight transportation, increased substantially in the last third of a century. Since 1980, gross domestic product (GDP) in the U.S. has increased by 140%[18] and air travel has increased by 134%.[19] Over the long term, it is expected that demand for air transportation will continue to grow. Current forecasts are for 2.3% per year growth of enplanements over the next two decades, resulting in 58% more passengers.[20] As a result, growth of the aircraft fleet and expansion and further development of existing airports are expected. This also means that emissions from aviation activity are expected to increase unless the improvements in operational efficiency, sustainable alternative fuels, and associated low-emissions technologies discussed below can offset that growth.

Trends in Aviation Emissions.

While aviation activity is forecasted to grow, emissions are also dependent on other factors including:

- Aircraft construction materials and technological sophistication – the lighter, more aerodynamic and technologically sophisticated an aircraft is, the less fuel it will use.
- Aircraft operations – the less time an aircraft spends taxiing or idling on the ground and the more direct routing a flight can take, the less fuel it will use. Restricted or congested air space, adverse weather, congested airports, and inefficient ground operations can all result in increased emissions.
- Fuel composition – while they are needed in small quantities, the presence of sulfur and heavy or complex hydrocarbon molecules such as aromatic compounds create particle pollutants and reduce combustion efficiency.

As demonstrated by the fuel efficiency trends in Figure 1, technological advancement in aircraft engine design has reduced aircraft fuel consumption and emissions on a per flight basis significantly over the past several decades. During this same era, the industry developed and deployed new, lightweight, high-strength materials, automated navigational, operational, and engine control systems, and employed vast new computational capabilities to improve aerodynamic efficiency and integrate highly complex operational structures such as hub and spoke airport networks. Jet aircraft in service today are over 70% more fuel efficient per seat-kilometer than the first jets in the 1960s.[21]

Although new aircraft are significantly more fuel efficient, average fuel economy for the worldwide commercial aircraft fleet improves slowly because commercial passenger service aircraft typically remain in the fleet for 30-35 years. As they age, existing aircraft are retired and replaced with new aircraft as illustrated in Figure 3: Growth and Replacement of Passenger Aircraft. New aircraft also are added to the fleet for new capacity. In 10 years, 52% of the fleet will be new aircraft, increasing to 86% in 20 years. These new aircraft will incorporate advanced technology and capabilities with a corresponding improvement in fuel efficiency.

Figure 3: Growth and Replacement of Passenger Aircraft
Worldwide fleet growth and replacement forecast based on historic aircraft retirement for large commercial aircraft [22]

The FAA today is focused on transforming the Nation's airspace system. The Agency has launched the NextGen program,[23] which will overhaul the nation's air traffic control system. Significant effort is going into reducing congestion and delay. The planned improvements will also increase system reliability. These changes will speed up the reductions in emissions on a per flight basis.

Efforts are underway to improve the jet fuel being used, which has the effect of reducing emissions. New alternative fuels such as those produced from biological materials could dramatically reduce aviation CO_2 emissions. By tailoring fuel quality to engine design aircraft will be able to produce fewer emissions per flight. Jet fuel issues are the subject of research by the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) program. Recently completed Project 28 (Environmental Cost-Benefit Analysis of Alternative Jet Fuels)[24] has significantly improved understanding of the environmental costs and benefits of alternative jet fuels. It evaluated life cycle greenhouse gas emissions from alternative jet fuels on a screening level, developed a first-order fuel production cost model, developed alternative fuel usage scenarios that deliver specified greenhouse gas reductions and expanded the environmental analysis to consider sustainability in terms of land, water, and air. The sustainability assessment started under Project 28 is the primary basis for ongoing research extending the applicability of that assessment to additional technology sets and feedstock options, to develop scenarios for biofuel deployment, and to conduct tradeoff analyses among different metrics and options. Alternative jet fuel sustainability has become a focused topic for research by the FAA. The results of this work are relevant to the NextGen environmental and energy goals relating to the development of alternative jet fuels, and offer important information to regulators, fuel producers and fuel procuring agencies as to the overall sustainability of different feedstock and technology options.

Emission Impacts

Aviation emissions affect both air quality and the global climate. Compared to other economic sectors, commercial aviation is a relatively small contributor to emissions of concern for both air quality and climate change. However, aviation emissions occur in the climatically sensitive upper troposphere and lower stratosphere where they may have a disproportionate impact on climate. They also occur at high altitudes where their impact may be felt at large distances away from where they are released.

In this section we discuss how aircraft emissions affect human health and the environment and how they are regulated to limit harmful effects. There are three factors to consider in evaluating emissions' impacts: 1) The quantity and characteristics of emissions; 2) how humans and sensitive environments get exposed to them; and 3) their human health and environmental effects.

Measuring Aviation Emissions.

Aviation stakeholders, including the FAA, commercial airlines, airframe and engine manufacturers, NASA, EPA, and the U.S. military, have a long history of conducting research to measure the amount and composition of aviation emissions. In recent years there have been several emission measurement programs that have significantly increased the knowledge of aircraft emissions. The Aircraft Particle Emissions eXperiment (APEX)[25] tests were conducted between 2004 and 2006 and measured emissions throughout the power range of aircraft engines using a variety of fuels. The tests measured emissions at the exit of the engine as well as downstream in the exhaust plume as they cooled and mixed with ambient air to evaluate the chemical and physical changes that take place. Engines of various sizes were included in these programs. More recent tests have measured emissions from other aviation sources such as APU, GSE, and aircraft tires and brakes.

Knowing the amount and characteristics of the emissions from various aviation sources is only part of the story. It is also important to know about their combined emissions at airports. The FAA,[26] commercial airports, the U.S. military,[27] National Academy of Science Transportation Research Board,[28] and other stakeholders have carried out several projects that measured emissions and air quality in and around airports. Measurements have been conducted on airports, in communities adjacent to airports, and downwind of airports for airports ranging from large hub airports to small, local airports.

Over the past decade many more projects[29] have measured and characterized aviation emissions. These projects have helped researchers understand where emissions are released, what they are made of and how they change chemically and physically, how they disperse in the air, and where they end up.

Today a great deal is understood about the amount and type of emissions that come from aviation operations. However, tracking emissions from a wide variety of sources operating simultaneously, which are spread out over an airport, and which are being influenced by changing operating schedules and the dynamic effects of variable weather, is challenging. To make sense of all of the measurement data and information that has been gained about emissions, powerful tools have been developed that help to track and assess the impacts of aviation emissions.

Modeling Emissions and Exposure.

Computer models are the tools we use to assess environmental effects. The first models were simple and quantified emissions from individual sources. In the past decade, FAA has developed a suite of software tools that allow for a more thorough assessment of the environmental effects of aviation. NASA, Transport Canada, industry, and academia aided this multi-year development process.

The focus of this development effort has been to incorporate the best scientific understanding into the tools, by building on the body of data from the measurement programs. After quantifying emissions from multiple sources over a common time period, current models show how weather and other atmospheric conditions cause the emissions to migrate or disperse into the environment. Adding dispersion capabilities was a significant milestone in model development. Dispersion analysis allows the modeler to calculate the concentration of emissions at various points on and off the airport. This in turn shows the degree to which passengers, citizens living nearby, and the local community are exposed to aviation emissions. Furthermore, these tools can provide a before-and-after comparison of pollutant concentrations for planned airport improvements as a way of demonstrating project impacts.

The primary building block of this new suite of software tools is the Aviation Environmental Design Tool (AEDT)[30], which integrates existing noise and emissions models and helps assess interdependencies. AEDT is currently used by the U.S. Government for domestic planning, environmental compliance, and research analysis. Another element of the suite, targeted to the government research community, is the assessment of aircraft performance using tools such as Environmental Design Space (EDS)[31] Piano (Project Interactive Analysis and Optimization)[32], TASOPT (Transport Aircraft System OPTimization[33], and SUAVE (Stanford University Aerospace Vehicle Environment)[34]. These tools are used to address different types of questions that are being asked. EDS is an aircraft and engine analysis tool capable of estimating source noise, exhaust emissions, performance and economic parameters for future aircraft designs under different technological, operational, policy, and market scenarios. EDS can assess interdependencies between noise, emissions, and performance at the aircraft level. PIANO is used to extract aerodynamic and performance data for aircraft manufactures that did not provide this data. TASOPT was used in PARTNER Project 48 [35](Development of a Distributed Approach to System Level Uncertainty Quantification) in the creation of a new aircraft conceptual design capability in the FAA tools suite and in developing an approach to perform a system-level quantification of uncertainty. SUAVE is a design tool that allows for an arbitrary aerospace vehicle to be designed with an arbitrary level of fidelity in its supporting data. It was used in PARTNER Project 43 (Analysis of Mission Specifications).[36]

This allows FAA to analyze fleet level impacts of future aircraft designs. To complete the suite of tools, the Aviation Environmental Portfolio Management Tool (APMT) is under development. Initially targeted for government use, APMT adds environmental impact and economic analysis capabilities to the tool suite.[37]

Each model in this environmental tools suite can be run independently, to allow focus on specific aspects of the analysis, but also can operate in an integrated fashion. This current suite of tools provides the ability to characterize and quantify aviation emissions, impacts on health and welfare, and industry and consumer costs, at local, regional, national and international levels. Users can assess different policy, technology, operational, and market scenarios and also evaluate the interdependencies between emissions and noise and understand the cost impacts. With this suite of models, different options for mitigating the impacts of emissions can be evaluated. For example, FAA can assess the environmental benefits of air traffic management system modernization alternatives, evaluate new engine and airframe designs, and assess health and economic impacts from the use of alternative fuels. The models also allow the FAA to coordinate with foreign counterparts through the International Civil Aviation Organization (ICAO), a United Nations intergovernmental body responsible for worldwide planning, implementation, and coordination of civil aviation, and ICAO's Committee on Aviation Environmental Protection (CAEP).[38]

Aviation Emissions and Air Quality.

Particulate matter, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead are common air pollutants found in the atmosphere across the United States. These pollutants can harm human health and the environment, and cause property damage. Of the six pollutants, particle pollution and ground-level ozone are the most widespread health threats. EPA regulates ground-level ozone, which is not emitted directly but is formed when nitrogen oxides and hydrocarbons react in the atmosphere in the presence of sunlight. Since 1980, total U.S. emissions of certain air pollutants EPA regulates (NO_x, SO_x, PM, CO, and lead (Pb)) have declined significantly, according to their 2012 report *National Emissions Inventory (NEI) Air Pollutant Emissions Trends Data*.[39] As shown in Figure 4, NO_x decreased 46 percent, sulfur dioxide (SO_2) emissions have decreased 63 percent, and emissions of particles less than 2.5 micrometers ($PM_{2.5}$) declined by 11 percent. At least half of these reductions occurred within the last five years. In spite of these successes, ground-level ozone and particles less than 2.5 micrometers ($PM_{2.5}$) continue to present challenges in many areas of the country.[40]

Total national pollutant emissions do not tell the full story with regard to aviation's contribution in regions with air quality problems. EPA data confirms that the worst air quality generally occurs in and around cities, which is also where aviation activity primarily occurs. The Clean Air Act, which will be discussed in further detail later in the document, requires EPA to determine whether regions within the U.S. comply with (i.e. attain) National Ambient Air Quality Standards (NAAQS).[41] Many U.S. airports are in nonattainment areas: 43 of the 50 largest airports are in ozone (O_3) nonattainment areas and 12 are in $PM_{2.5}$ nonattainment areas.[42] Aviation's contribution to a region's air emissions inventory is generally small, as is shown in Table 2.[43]

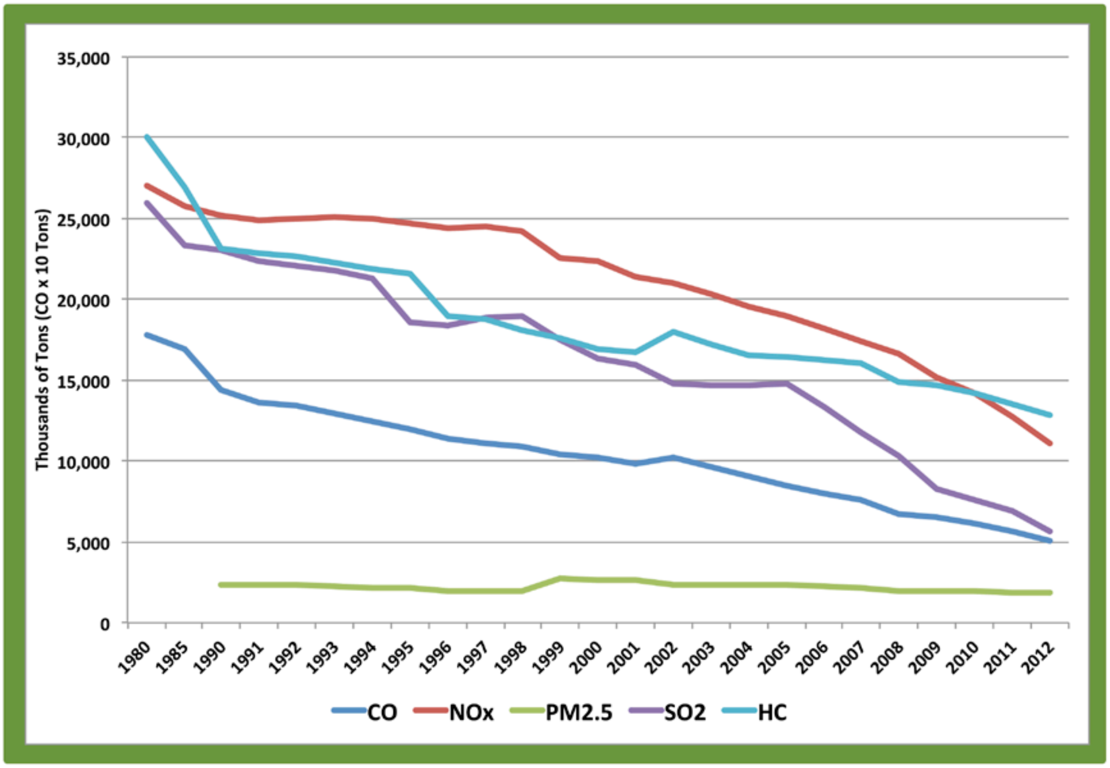

Figure 4: U.S. Pollutant Emissions from All Emission Sources
U.S. annual pollutant emissions[44]

According to the National Environmental Policy Act, airport construction projects that are funded with public dollars must not interfere with a region's ability to attain the NAAQS. For capacity enhancing projects, emissions mitigation projects may be necessary for an airport expansion to proceed. Such projects may include converting airport shuttle buses and other vehicles to low emission alternative fuels such as compressed natural gas or electricity, installing gate electrification and preconditioned air services so that aircraft do not have to run their auxiliary power units when parked at the gate, or installing solar energy panels to produce electricity.

In the past few years, scientists have hypothesized that aircraft emissions released at cruise altitude, particularly SO_x and NO_x, are likely to produce additional secondary PM that is transported very long distances (continent to continent) and then deposited to the surface of the Earth to affect air quality.[45] These results need to be confirmed to understand the significance of these emissions. FAA has several research projects underway to better understand the science and mechanisms involved and to quantify local air quality impacts from cruise emissions.[46]

Aviation Emissions and Climate Change.

Concern regarding greenhouse gas emissions has been building worldwide. Total U.S. greenhouse gas emissions have increased at an average annual rate of 0.4 percent since 1990.[47] Transportation emissions in the U.S. have increased about twice that fast and by 2012 accounted for about 28% of total U.S. CO_2 emissions, as illustrated in Figure 5: U.S. Greenhouse Gas Emissions by Economic Sector. Aviation accounts for about 12% of transportation emissions, or 3.36% of total CO_2 emissions in the U.S.

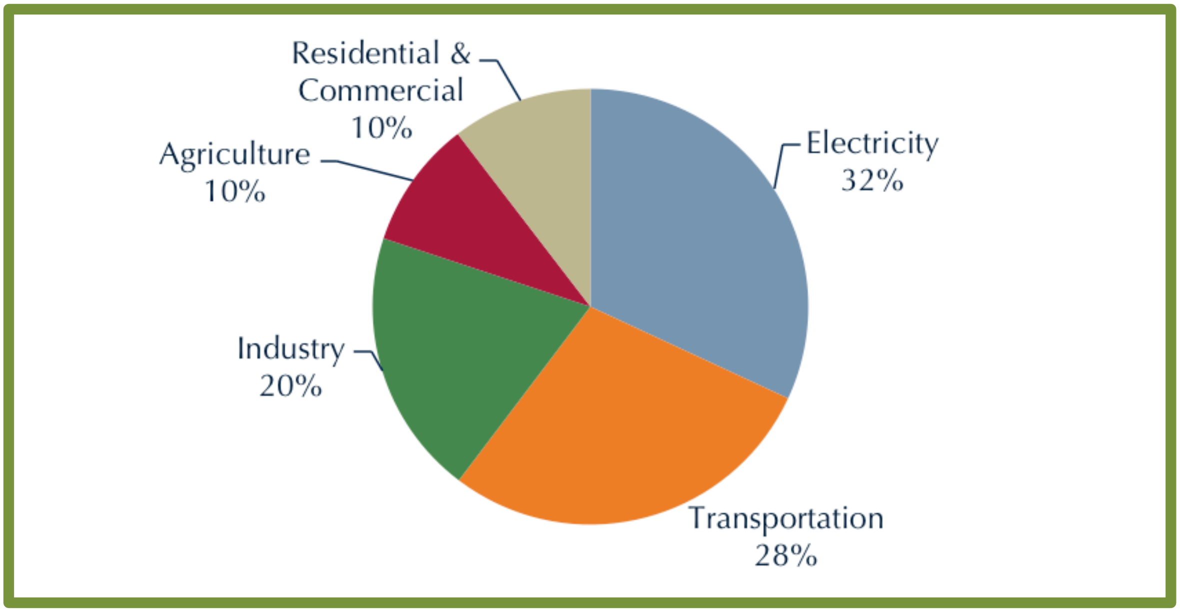

Figure 5: U.S. Greenhouse Gas Emissions by Economic Sector (2012) [48]

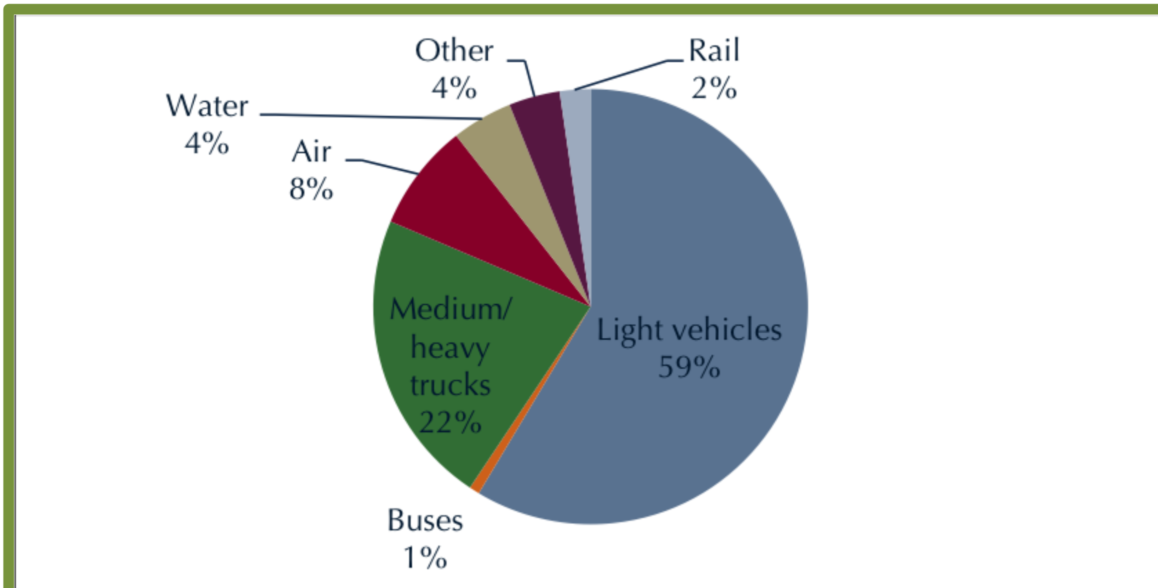

Figure 6: Transportation Energy Use by Mode (2012)[49]

Similarly the latest global climate research indicates that aviation's contribution to human-induced climate change is between 3.5% and 4.9%.[50] This share is forecast to increase to between 4.4% and 6.2%, by 2050[51] unless new technologies and policies are adopted to reduce aviation emissions. There remains a great deal of uncertainty in estimated impacts on climate change, which is being resolved through ongoing research efforts.[52]

The climatic impacts of aviation emissions are quite complex and include direct climate effects from CO_2 and water vapor emissions, the indirect effect on climate resulting from changes in the distributions and concentrations of O_3 and methane (CH_4) due to NO_x emissions, the direct effects (and indirect effects on clouds) from emitted aerosols and aerosol precursors, and the climate effects associated with contrails and cirrus cloud formation.

Climate effects are due to interaction with solar and thermal radiation by gases such as carbon-dioxide and water vapor (see Figure 7 below), as well as pollutants such as CO, HC and black carbon (BC) particles arising from incomplete combustion in the gas turbine combustor. SOx emissions form sulfuric acid in the presence of water vapor, which further interacts with ammonia (NH_3) in the Earth's boundary layer to form ammonium sulfate particles. NOx emissions affect the formation of ozone and form nitric acid (HNO_3) at cruise altitudes and ammonium nitrate particles in the boundary layer in the presence of ammonia, thus affecting air quality. The soot particles at cruise altitudes interact with other chemicals such as sulfuric acid and nitric acid to form small particles that act as nucleating sites for condensation of water vapor present in the upper atmosphere under certain conditions to form larger particles to form condensation trails or contrails, for short. These contrails are visible along flight tracks with a short lifetime around a few hours. At times, under the right meteorological conditions these contrails expand perpendicular to the flight tracks to form contrail-induced cirrus clouds that also interact with shortwave and longwave radiation, thus affecting climate.

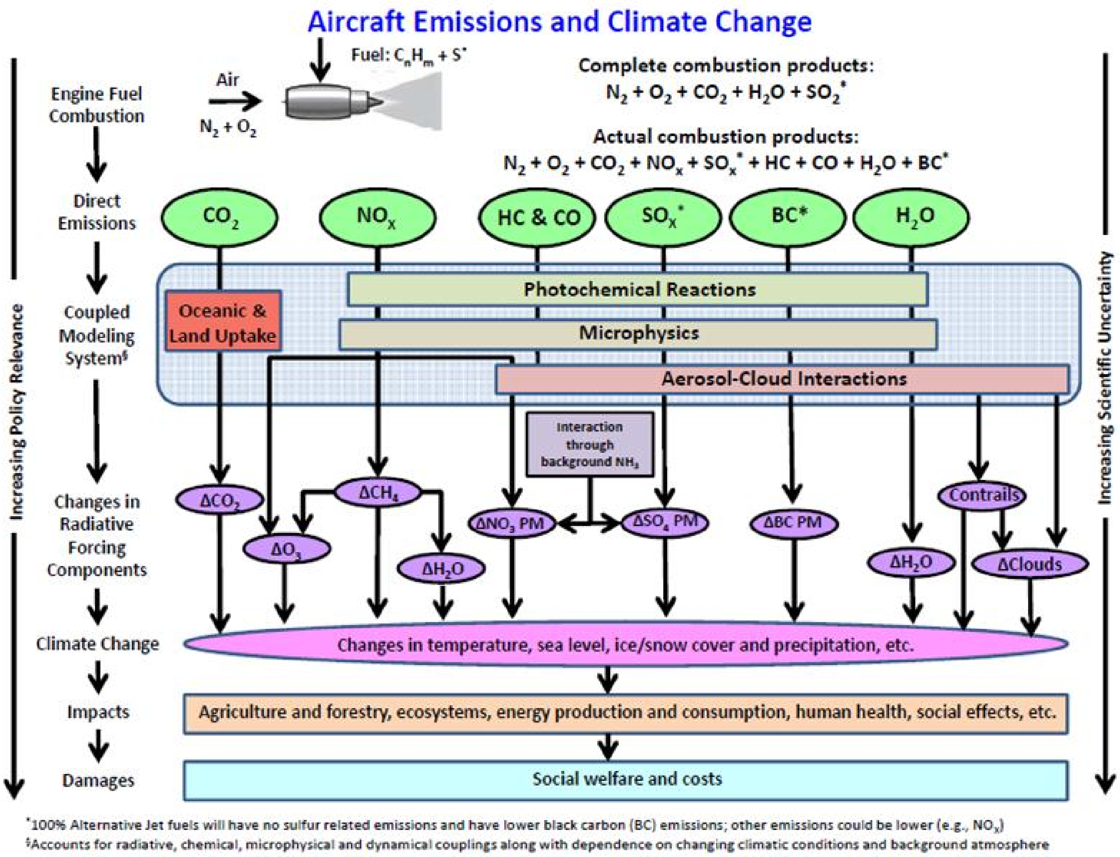

Figure 7: Schematic representation of emissions from aircraft combustion[53]

Atmospheric and climate system interactions (e.g. chemical, microphysical, dynamical and radiative) of aircraft emissions remain poorly understood and require more research. Figure 7 is a graphical representation of the current understanding of the potential climate and social welfare impacts of emissions from aircraft combustion.

The figure above also shows policy implications at various stages of these emissions, with increasing policy relevance downward. The formation of gases and particles that interact with radiation affect climate and air quality at the surface. Minimization of these products is therefore desirable. Mitigation options such as altering the routes to prevent formation of contrails, redesigning engine combustors with high bypass ratios to reduce temperatures to minimize formation of NOx, and reducing impurities such as sulfur in the fuel to minimize formation of particles are all examples of results of policy decisions to minimize climate impacts. Ultimately such actions result in reducing the costs to the society and increase social welfare in the form of impacts on health and wellbeing.

Regulation of Aviation Emissions.

A wide range of environmental regulations applies to airport activity and equipment. Aircraft engines have certification requirements for CO, HC, NO_x, and smoke emissions. Ground access vehicles are subject to tailpipe emission standards, and GSE may be subject to nonroad engine standards. The composition of jet fuel, diesel fuel, and gasoline are all regulated to limit harmful emissions, ensure proper performance of engines and fuel systems, and avoid engine durability concerns. The reduction in the level of sulfur in gasoline is justified by its known reduction in the efficiency of catalytic converters, which means these devices are less capable of removing emissions from exhaust gases. Thus, removing sulfur is a means of reducing other emissions of toxins from ground vehicle exhausts. Reduction of naphthalenes in fuel reduces the formation of carbonaceous particles that are potentially harmful, because they can cause erosion on turbine blades and form hot spots that can lead to premature engine failure. Many operational activities and equipment require permits. The FAA must consider the air quality impact of actions it undertakes, licenses, or funds and determine that airport expansion plans conform to regional air quality plans.

The Clean Air Act (CAA)[54] is the primary, overarching air quality law in the U.S. The CAA establishes EPA as the agency responsible for setting appropriate air quality standards and developing regulations to meet those standards. EPA sets standards for ambient air quality in geographic regions that generally represent metropolitan areas. Under the CAA, EPA sets the NAAQS for NO_2, SO_2, $PM_{2.5}$, CO, O_3 and lead (Pb). EPA sets most regulatory standards but many permitting programs are administered by state agencies. With respect to aircraft engines, the CAA requires EPA to consult with the FAA and provides the FAA with the authority to enforce EPA's aircraft engine emissions standards through its certification regulations.[55] FAA is responsible for ensuring these regulations do not pose conflicts with safety and other aircraft operational requirements. For example there are more than 60 standards[56] that apply to aircraft engine design, materials of construction, durability, instrumentation and control, and safety, among others. These are in addition to the Fuel Venting and Exhaust Emission Requirements for Turbine Engine Powered Airplanes,[57] which specify compliance with EPA's aircraft exhaust emission standards.

The National Environmental Policy Act of 1969 (NEPA)[58] requires federal agencies to consider the environmental impacts of their actions, which could include grants, loans, leases, permits and approval of plans or projects. NEPA applies to most airport construction projects as a result of FAA funding or approval. Some actions that are subject to NEPA review also trigger the CAA's "general conformity" provision, which seeks to ensure that actions approved by the federal government do not interfere with a region's plan to meet air quality standards.[59] Federal agencies must ensure that proposed project emissions from Federal actions at airports located in nonattainment areas "conform" to the applicable State Implementation Plan.

Internationally, ICAO has long been the forum for evaluating the environmental performance of aircraft engines. ICAO has taken a "technology progressing" approach, raising standards within the capabilities of proven technologies and certified products (engines and aircraft) rather than a "technology forcing" approach, which would set standards based on technology that is not certified or may not even exist. The reason for ICAO's approach is quite simple – the very high premium placed on the safety of aircraft operation restricts the use of unproven new technologies.

Health and Environmental Effects of Aviation Emissions.

Particulate Matter (PM).

The FAA continues to sponsor research[60] to understand and evaluate how aviation emissions contribute to local and regional air quality, through a combination of measurement and modeling studies using the most advanced computer tools, and to evaluate the potential incremental health risks due to air pollutants such as particulate matter, ozone, and hazardous air pollutants. This research has built on the extensive health impacts research undertaken over many years by EPA and medical research organizations. Research to date indicates that fine particulate matter is responsible for the majority of the health risks from aviation emissions, although ozone also has a substantial health impact too. A comprehensive health impacts analysis should include the impacts of ozone and other pollutants as well.[61]

Throughout the transformation process, particles form in various sizes. As a general rule, the smaller the particle the further it travels in the atmosphere, the longer it remains suspended in the atmosphere, and the more risk it poses to human health. Particulate matter includes both primary PM, which is directly emitted into the air, and secondary PM, which is formed through physical and chemical atmospheric processes. $PM_{2.5}$ can be readily inhaled and thus potentially pose increased health risks. These particles are too small to readily settle out of the atmosphere. They can be transported thousands of miles and remain in the atmosphere for days to weeks.[62] Additionally, fine particles suspended in the atmosphere absorb and reflect light, which is the major cause of reduced visibility (haze) in parts of the United States. Ultrafine particles are a subset of $PM_{2.5}$, measuring less than 0.1 micrometer in diameter.

There are multiple health effects associated with exposure to PM, including impacts to the respiratory, cardiovascular, and neurological systems.[63] Smaller particles less than 2.5 micrometers in diameter, which are typical of aviation emission, tend to pose higher risk since they migrate deeper into the lungs and bloodstream causing cardiovascular effects and even affecting the nervous system. Human exposure to small particles can aggravate heart and lung disease resulting in increased hospital admissions, emergency room visits, and absences from school or work. Older adults, children, and people with heart or lung disease are the most sensitive to exposure to PM.

Preliminary research suggests that of the premature mortalities related to emissions from all combustion sources, less than 1% are associated with aviation emissions.[64] In the future, the relative health risks of aviation emissions will be strongly influenced by changing background pollutant concentrations and population growth as well as changing non-aviation emissions.

EPA set the first PM standards[65] in 1971. The standards were revised in 1987, 1997, 2006, and again in 2013.[66] EPA no longer regulates particles larger than 10 micrometers (e.g., sand and large dust), which was the focus of the original standards, since they are not deemed readily inhalable. The local PM concentration is the sum of all regional sources of PM and the regional ambient background. PM emissions from airports and other regional sources mix relatively quickly with the ambient background PM. The combination of emissions from airports and other regional sources and ambient concentrations of PM result in a combined atmospheric PM loading that depends on complex atmospheric processes, including chemical reactions and pollution transport. This makes it difficult to isolate the contribution of airport activity from all other emissions sources in an area.

In addition to the CAA's NAAQS there are other regulations that directly or indirectly effect PM emissions from aviation. For example, ICAO has established aircraft engine certification standards[67] that limit smoke emissions, as measured by "smoke number."[68] The smoke standards took effect in 1983. Since smoke is an indicator of PM emissions, these standards have been indirectly influencing aircraft PM emissions for the past 30 years.

As described earlier, sulfur in jet fuel combines with oxygen from the air during combustion, producing SO_2, a portion of which eventually produces secondary particulate matter. Sulfur emissions are directly related to the sulfur content of the fuel. Internationally accepted standards[69] for Jet A, which is the commercial aviation fuel used in the US, limit fuel sulfur content to 0.30% wt. (3,000 PPM S) maximum. In practice, however, weighted mean sulfur levels for Jet A sulfur measured in the 2010 survey are well below the typical maximum specification limit. The four month averaged weighted mean sulfur level on the overall U.S. was 544 PPMS, a 23% drop from the 2007 to the 2010 levels.[70]

EPA has required diesel fuel suppliers for nonroad equipment to reduce fuel sulfur content to the same ultra-low sulfur limits required for on-road diesel. This allows the nonroad equipment to use advanced emission control technologies. These requirements for diesel fuel sulfur limits and engine emission standards will reduce PM emissions from nonroad equipment by 90%.[71] GSE using alternative fuels such as compressed natural gas and propane have 25% lower PM emissions[72] and those powered by electricity[73] have no PM emissions.

In 2007, EPA proposed new exhaust emission standards[74] for non-road diesel engines. These standards are being phased in between 2008 and 2014 and require engine manufacturers to produce new engines with advanced emission control technologies. New GSE with diesel engines are required to meet these standards. This new equipment achieves emission performance comparable to today's automobiles.

Stationary emission sources at airports include various facilities and equipment like boilers, emergency generators, incinerators, fire training facilities, and fuel storage tanks. Many of these equipment types require specific operating permits with PM emission limits. Stationary sources typically represent about 1-2% of PM emissions at airports.[75] Individual particle species that do not appear to be harmful may be so when occurring in a mixture. PM can be solids, like dust, ash, or soot, and it can also be completely liquid aerosols or solids suspended in liquid mixtures.[76] Measures to reduce particles will reduce all components of the mixtures. Batteries of scientific studies have linked particulate matter, especially fine particles either alone or in combination with other air pollutants, with a series of significant health problems. The relation to adverse health effects has made fine particulate matter of primary concern in aviation studies. These are topics for ongoing and future research.[77]

Oxides of Nitrogen (NOx).

ICAO has established international certification limits[78] for oxides of nitrogen (NO_x) emissions from jet engines that limit the amount of NO_x emitted. EPA has adopted ICAO's certification standards as national regulations.[79] FAA, in turn, enforces these standards through engine certification.

Current NO_x emission standards for aircraft engines were established in 2012[80], which is a tightening of the prior standards. This is the fourth change since the original standards were agreed to in 1981. New standards went into effect for engines entering service beginning in 2013, which reflect a 12 percent NO_x reduction over the 2008 standards. ICAO's CAEP has since recommended new certification standards that represent a further 15 percent NO_x reduction, with an effective date of 2014.[81] For aircraft, new NO_x certification standards are being considered that will reduce their total NO_x emissions. Aviation NO_x emissions are still projected to be less than 3 percent of the transportation NO_x inventory by 2020.[82]

While there currently are no national or international regulations for greenhouse gas emissions that apply to aircraft or other airport sources, the aviation industry has made significant strides here as well. Aircraft have a long history of continuously improved fuel efficiency (measured in fuel use per passenger mile), which reduces all greenhouse gas emissions. For example, according to Boeing, the Boeing-787 is 20 percent more efficient than the Boeing-767, which it succeeds[83] and the Boeing-737N (the Max) burns 14% less fuel than today's Beoing-737-800NG.[84] Fuel efficiency and energy conservation are also priorities at many airports.[85]

Future Regulations.

The FAA is working through ICAO to evaluate policy options to limit or reduce greenhouse gas emissions from international aviation. ICAO has developed a range of standards, policies and guidance material for the application of integrated measures to address aircraft noise and engine emissions. Efforts include progress on new aircraft technology advancement, operational improvements and development and deployment of alternative fuels, as well as a commitment to develop a global market-based measure for international aviation and appropriate airport and land-use planning. Through the ICAO's CAEP, FAA is supporting development of an aircraft CO_2 emission standard. The standard is expected to reduce aircraft CO_2 emissions by integrating fuel-efficient technologies into aircraft design and development. It has been developed such that effective improvements observed through the CO_2 standard will correlate with reductions of CO_2 emissions by aircraft during day-to-day operations. CAEP is developing an aircraft engine PM certification standard as well.

In October 2013, the 38th ICAO Assembly adopted a comprehensive climate change resolution that includes a commitment to develop a global market-based measure to address GHG emissions from international aviation. The U.S. is committed to pursuing development of a global market-based measure (MBM) proposal. It has to be considered as gap filler in the basket of measures that includes technology, operations and alternative fuels. These efforts contribute to achieving ICAO's aspirational goal of carbon neutral growth by 2020 using a 2005 baseline. The U.S. is engaged both in supporting policy and technical work contributing to the proposal for a global MBM.

Under this multidimensional regulatory and voluntary structure, aviation has made significant environmental progress. Given the complexity of the industry and the need for different strategies and technological approaches for different types of vehicles and equipment, a coordinated effort will continue between the aviation industry and the many regulatory agencies that share environmental responsibilities.

Mitigating Aviation Emissions

The efficiency of each part of the National Airspace System (NAS) affects the production, and resultant impacts, of aviation emissions. Each of the NAS parts -- aircraft operations, aircraft materials and technologies, and fuel composition -- has made significant advances in mitigating emissions over the past decade. Regulations are in place to limit harmful effects of aviation emissions on human health and the environment. The FAA, in working closely with industry and other government agencies, continues to invest significant resources into research and technology development to improve emissions mitigation. This section describes FAA's approach to addressing environmental concerns and details some of the future research and development activities.

STRATEGY FOR REDUCING AVIATION EMISSIONS – Five-Pillar Environmental Approach.

FAA sets its specific goals for environmental initiatives based on the latest scientific understanding of aviation's environmental impacts. The Agency relies on a five-pillar comprehensive and integrated approach to set the specific initiatives needed to achieve aviation environmental goals.

PILLAR 1: Improved Scientific Knowledge and Integrated Modeling.

Aviation environmental analyses, impact determinations, and mitigation decisions for NextGen activities must be based on a solid scientific foundation. This requires continued investments in research to improve scientific understanding of the impacts of aviation. In addition, developing and using advanced decision-support tools that account for interdependencies of impacts and cost-benefit analyses of potential solutions facilitates more informed decision-making. Prospective solutions and combinations of solutions have different impacts, benefits, and costs. Some solutions optimize for one area of environmental protection at the expense of another; where trade-offs are made they are explicitly defined and as transparent as possible.

Centers of Excellence (COE). The FAA has long had a successful partnership with the nation's academic research community, working with more than 75 U.S. colleges and universities to foster important research conducted by faculty and students. For almost two decades, these efforts have contributed significantly to advancing aviation science and technology while providing the agency and the industry a high return on investments. Through FAA COEs, the government, academic institutions, and industry leverage the combined resources available for aviation research and maximize technological competence for public purpose.

Alternative Fuel Effects on Contrails and Cruise Emissions (ACCESS). NASA initiated the ACCESS program as a follow-on to the APEX emissions measurement projects as part of their Fundamental Aeronautics Aviation Emissions Research program. With FAA's active participation, the first ACCESS project sampled aircraft cruise emissions with inflight testing of a 50/50 blend of an alternative jet fuel and conventional jet fuel. Tests were conducted over a range of power-settings at different altitudes. Also extensive measurements of ice particle size and concentrations were made to evaluate contrail formation.

Additional alternative jet fuel testing and inflight emissions measurements will be part of future ACCESS projects conducted in the next few years. These projects may also provide an opportunity to verify the models used to evaluate aviation emissions impacts.

Aviation Emissions Characterization (AEC) Roadmap. The AEC Roadmap is a unified regulatory research and development (R&D) roadmap for understanding and quantifying aircraft emissions. FAA, NASA, DOD, and EPA all are members of the AEC Roadmap Coordination Council. There is collaboration on the roadmap with manufacturers, airports, airlines, and other stakeholders. The Roadmap coordinates research activities and communicates research findings among stakeholders and other parties with an interest in PM, hazardous air pollutants (HAP), and other emissions from aviation sources. The Roadmap's objective is to gain the necessary understanding of emissions' formation, composition, and growth and transport mechanisms to assess aviation's emissions and understand their impact on human health and the environment. The AEC Roadmap does not fund research projects but it does help agencies identify research priorities and leverage their budgets to accomplish more than they would otherwise.

Airport Cooperative Research Program (ACRP). FAA funds an industry-driven, applied research program that develops near-term, practical solutions to problems faced by airport operators. The Transportation Research Board (TRB) of the National Academy of Sciences manages ACRP. The program carries out applied research on problems that are shared by airport operating agencies, which may not be adequately addressed by other federal research programs. A substantial number of ACRP projects have addressed environmental concerns ranging from emissions measurement campaigns to model development and enhancement to practical guidance to airports for improving their environmental performance. Of FAA's $15 million annual funding for the ACRP, $5 million is allocated for environmental projects. Since the ACRP is identified in FAA reauthorization legislation,[86] it is anticipated that this program will continue in the future.

Aviation Climate Change Research. In 2010**,** FAA initiated the 3-year Aviation Climate Change Research Initiative (ACCRI) program under its climate change research program to evaluate the impacts of aviation emissions on climate change from a 2006 baseline and into the future (2050). It evaluated the effects of aerosols, induced contrail effects, contrail-induced cirrus effects, and aerosol indirect effects. In addition to the tools FAA developed, this research used a number of large-scale general circulation models and simple-climate models, satellite and laboratory measurements, and detailed aerosol and ice-particle microphysical models. This research recognized the potential impact of indirect aerosol and contrail effects. Quantifying these impacts is the subject of ongoing current climate research.[87] The current scientific opinion as expressed in this effort emphasizes the need to lower uncertainties while characterizing the aviation chemical and physical impacts on climate. Additional studies are currently underway in analyzing data from 2012 to estimate their reliability and accuracy.

***PILLAR 2: Air Traffic Management Modernization*.**

Developing and integrating advanced operational procedures and infrastructure improvements enhances operational capabilities that function more efficiently, improving energy efficiency and thus mitigating environmental impacts. Air traffic management modernization and improvements being made as part of NextGen increase the efficiency of aircraft operations, both in the air and on the airport surface. Improving efficiency saves time and fuel. Reducing fuel consumption reduces CO_2 emissions that affect climate and other emissions that adversely affect air quality. Performance Based Navigation (including area navigation (RNAV) and required navigation performance (RNP)) routes can cut fuel burn, emissions, and flight times. Optimized Profile Descents (OPD) can reduce noise, emissions, and fuel consumption. New technology and procedures that optimize gate-to-gate operations are being demonstrated with international partners in Europe and Asia-Pacific to reduce fuel burn, emissions, and noise. One of the most significant programs for improving operations is NextGen.

Transforming the Air Transportation System – NextGen. FAA has begun the transformation of the air transportation system through NextGen a metamorphosis of the air traffic control system. The FAA's environmental vision for NextGen is to provide environmental protection that allows sustained aviation growth. NextGen will provide many opportunities for accomplishing emission mitigation goals by giving impetus to and accommodating changes that are needed for system efficiency and operational improvements. FAA is developing NextGen capabilities that will guide and track aircraft more precisely and efficiently in the air and on the ground to save fuel, decrease emissions and manage the impact of noise on communities. In addition, the Agency is advancing efforts to reduce aircraft fuel burn, emissions, and noise through innovative aircraft technologies. In this way, FAA's environmental goals mesh well with the broader agency goals.

PILLAR 3: New Aircraft and Airport Technologies.

Historically, new technologies have offered the greatest success in reducing aviation's environmental impacts. New engine and airframe technologies continue to play key roles in achieving aviation environment and energy goals. The FAA and other agencies support advances in engine technology and airframe configurations to lay the foundation for the next generation of aircraft. Its technological strategy envisions a fleet of quieter, cleaner aircraft that operate more efficiently with less energy. The FAA and NASA, along with the Department of Defense, closely coordinate efforts on aeronautics technology research through the National Aeronautics Research and Development Plan. Each agency focuses on different elements but they share the same national goals. The FAA's focus is on maturing technologies for near term application while NASA focuses on a broader range of time frames of technology development. FAA's Continuous Lower Energy, Emissions and Noise (CLEEN) program is a NextGen effort to accelerate development and commercial deployment of environmentally promising aircraft technologies and sustainable alternative fuels. The aircraft technologies focus on reduction in aircraft noise, emissions, and fuel burn. Under this program, FAA has awarded five-year agreements to Boeing, General Electric, Honeywell, Pratt & Whitney, and Rolls-Royce. The total federal investment is expected to be $125 million over five years.

Continuous Lower Energy, Emissions, and Noise (CLEEN). The CLEEN program is a five-year effort to accelerate technology development. Advancements from the program reduce aircraft emissions, fuel burn, and noise through a cost shared initiative between FAA and industry where companies provide at least 50% or greater funding.

CLEEN has demonstrated engine technology that reduced landing and takeoff NO_x emissions by more than 60 percent below the ICAO standard adopted in 2004. It is also developing aircraft technology that contributes toward a 33% aircraft fuel burn goal relative to current technology with commensurate energy consumption and greenhouse gas emission reductions. Improved engine technologies, avionics, aircraft aerodynamics, and weight-related technologies also are being developed that will reduce aircraft fuel burn further. These achievements are expected to appear in the commercial airline fleet in the next several years.

CLEEN has also made significant contributions in the development and deployment of alternative jet fuels that are a drop-in replacement to fuels derived from petroleum. Alternative jet fuels are being tested to confirm the environmental benefits, technological feasibility, and economic cost. The efforts of CLEEN on aircraft technology maturation and alternative fuels development and deployment will help the FAA ensure that NextGen provides environmental protection that allows sustained aviation growth.

Following the success of the CLEEN program to date, FAA has established new goals for a second phase program, CLEEN II, from 2015 to 2020. CLEEN II will again have components focusing on emissions, fuel burn, and noise. New technologies, new aircraft designs, new system designs, and new alternative fuels from this program are expected to appear in use in the commercial fleet beginning at the end of this decade and will achieve reduced emissions, fuel burn, and noise in the decades to come.

Voluntary Airport Low Emission (VALE) program and Zero Emission Airport Vehicle and Infrastructure Pilot Program (ZEV). The FAA's Office of Airports has two specific programs underway to reduce emissions from ground support equipment and other airport vehicles. The VALE program[88] expands eligibility for airport low emission projects under the Airport Improvement Program (AIP) and the Passenger Facility Charges (PFC) program. Through the use of funding and emission credit incentives, the voluntary program supports converting airport vehicles and ground support equipment to low emission technologies, modifying airport infrastructure for alternative fuels, providing terminal gate electricity and air for parked aircraft, a pilot program to explore retrofit technology for airport ground support equipment, and other related emissions improvements. Between 2005 and 2012, more than $146 million[89] from AIP, PFC, and local matching funds has been invested thorough the VALE program to reduce airport emissions.

The ZEV program[90] allows FAA to award AIP funds to airports to purchase zero emissions vehicles and make infrastructure changes necessary to charge or otherwise fuel these vehicles. Authorized in 2012, the ZEV program encourages the use and development of electric and hydrogen fuel cell vehicles. There are a wide variety of vehicles used at airports, from automobiles and vans to large passenger buses, and this program encourages manufacturers to develop zero emission alternatives to meet these needs.

PILLAR 4: Sustainable Alternative Aviation Fuels.

Developing and deploying sustainable alternative aviation fuels enables environmental improvements, energy security, and economic stability for aviation. The aviation industry is committed to converting its fuel supply to alternative fuels.[91] Government and industry are working cooperatively with coordinating mechanisms such as the Commercial Aviation Alternative Fuels Initiative (CAAFI) and are supporting alternative fuels research. Near term efforts include adding new classes of fuels to the approved alternative jet fuel standard by American Society for Testing and Materials (ASTM) International and conducting aircraft flight tests using alternative fuels to confirm their suitability and environmental benefits. To date, these efforts have led to the certification of three alternative jet fuel types by ASTM International. ASTM International D7566 specification[92] covers the manufacture of aviation turbine fuel that consists of conventional and synthetic blending components.

To date, three alternative jet fuels have been approved for blending with jet fuel by standard setting organization ASTM International. They include fuels from biomass, coal or natural gas known as Fischer-Tropsch (FT) jet fuel; fuel from fats, plant oils and greases known as Hydroproccessed Esters and Fatty Acids (HEFA) jet fuel; and, fuel from fermented sugars known as Synthesized Iso-Paraffins (SIP) jet fuel. At this time additional fuel types are under evaluation for future approval.

One of the hallmark efforts in this area is Farm to Fly, commenced in July 2010,as a result of the U.S. Department of Agriculture (USDA), Airlines for America, Inc. (A4A), and the Boeing Company (Boeing) signing a resolution formalizing their commitment to work together on the initiative. The FARM to FLY 2.0 program[93] will "accelerate the availability of a commercially viable and sustainable aviation biofuel industry in the United States, increase domestic energy security, establish regional supply chains, and support rural development." In April 2013, the USDA and FAA joined with industry partners from Airlines for America (A4A), Aerospace Industries Association (AIA), Airports Council-North America (ACI-NA), National Business Aviation Association (NBAA) and the General Aviation Manufacturers Association (GAMA) in an expanded "Farm to Fly 2.0" collaboration "to enable commercially viable, sustainable bio-Jet Fuel supply chains in the U.S. that are able to support the goal of one billion gallons of bio-Jet Fuel production capacity and use for the Aviation Enterprise by 2018. In July, 2014 the U.S. DOE also signed on as a partner to the agreement.

Commercial Aviation Alternative Fuels initiative (CAAFI). CAAFI[94] is a coalition of airlines, aircraft and engine manufacturers, energy producers, researchers, international participants, and U.S. government agencies formed to develop and deploy alternative jet fuels for commercial aviation. CAAFI's goal is to develop alternative jet fuel options that offer equivalent levels of safety and compare favorably on cost with petroleum based jet fuel, while also offering environmental improvement and security of energy supply for aviation. To date, CAAFI has seen three fuel development pathways approved by ASTM and more than 1500 international demonstration and commercial aircraft flights using alternative fuels. Since aviation is international in scope, highly integrated in its fuel supply chain, and has a significant ability to align and coordinate within the industry, it is a very promising first mover among customers for alternative fuels.

Unleaded Avgas Transition (UAT Plan). Almost all aviation gasoline (avgas) used to power piston engine general aviation aircraft is designated "100 low lead." 100 low lead contains small amounts of tetraethyl lead, which boosts fuel octane. High-octane fuels are required in many aircraft so that their piston engines will not "knock," which can cause severe engine damage. However, EPA and the Centers for Disease Control and Prevention (CDC) have found in the past decade that there is no safe level of lead in blood. For that reason, the aviation community and government are coming under pressure to eliminate lead emissions from aircraft. At the request of the aviation, petroleum, and other concerned interests, FAA has initiated and is implementing the UAT Plan, which calls for a two-phase approach to identifying and approving an operationally safe unleaded avgas. One component of the plan is formation of the Piston Aircraft Fuels Initiative, which is composed of members from FAA, general aviation industry, and petroleum interests who will fund and coordinate identification and approval of the most promising unleaded candidate fuels. At the same time EPA is working to gain a better understanding of aircraft lead emissions and potential exposure through monitoring, modeling, demographic, and other studies. FAA's goal is to have a replacement fuel for leaded avgas available by 2018,[95] which is usable by most general aviation aircraft.

PILLAR 5: Policies, Environmental Standards, and Market-Based Measures.

Developing and implementing appropriate policies, standards, programs, and mechanisms are critical steps in quickly integrating advantageous technology and operational innovations into the commercial fleet, the airport environment, and entire national aviation system. An example is the development of the NextGen Environmental Management System (EMS), which integrates environmental protection objectives into NextGen. Cooperative partnerships between government and industry focus effort and leverage funding in ways that are beneficial for aviation and good for the environment. Internationally, the U.S. is leading efforts at ICAO to limit and reduce international aviation emissions, most notably through development of an aircraft CO_2 standard and an engine PM certification requirement. ICAO has additionally agreed to explore more ambitious goals for the aviation sector including carbon neutral growth in the mid-term and reductions in the long term. The FAA is exploring the effectiveness of various policies, including economic incentives to limit and reduce CO_2 emissions. Additionally, to achieve environmental and energy goals beyond the near term, policies are needed that accelerate the integration of new technologies into the civil fleet compared to the normal rate of introduction and replacement.

Aviation Sustainability Center (ASCENT). FAA recently established a new Center of Excellence for Alternative Jet Fuels and Environment. ASCENT will explore ways to meet the environmental and energy goals for NextGen, which will provide environmental protection that allows sustained aviation growth.

ASCENT is structured as a cost sharing partnership with academia to provide R&D support to inform FAA's environmental commitments and aspirational goals.

To achieve the aspirational 2018 alternative jet fuels target of one billion gallons used[96] per year and help to ensure the wide spread use of sustainable alternative jet fuels in the longer term, ASCENT will assist the FAA and the community with research to develop viable supply as well as secure ASTM International approval of alternative jet fuels.

Partnership for Air Transportation Noise and Emissions Reduction (PARTNER). PARTNER, an FAA COE, was cosponsored by NASA, Transport Canada, the U.S. Department of Defense, and the U.S. Environmental Protection Agency. PARTNER was comprised of 12 universities,[97] and approximately 50 advisory board[98] members including aerospace manufacturers, airlines, airports, national, state and local government, professional and trade associations, non-governmental organizations and community groups. They were united to foster collaboration and consensus to jointly advance environmental performance, efficiency, safety and security.

As an incentive to collaboration, equal matches were required for federal funds granted to PARTNER. The universities provided some of these matching funds, but most were obtained from the organizations represented on the advisory board. This collaborative process fueled unique research efforts on emissions, operations, alternative fuels, noise, and policy evaluations involving a wide spectrum of participants. More than 48 research projects have been completed or are underway representing a total budget of more than $56 million over the past 10 years. With the completion of the PARTNER program, a new Center of Excellence, ASCENT, was established. Some of the PARTNER projects were transitioned, through a competitive process to ASCENT, discussed above.

Reducing Aviation Emissions in the Future.

FAA has made significant progress addressing environmental concerns through the strategy and programs it has created under the Five Pillar Environmental Approach. New engine designs and technologies, like those developed in the CLEEN program, are improving fuel efficiency further, while simultaneously reducing noise, NO_x and PM emissions. New aircraft designs are taking advantage of advanced computer models to improve operating performance and fuel efficiency, reducing all pollutants at the same time. New air traffic control technologies and operating practices are reducing emissions by reducing fuel consumption. Airports are using low emission equipment. And alternative jet fuels are being developed that will cut the impact of aviation on climate change and air quality significantly. More progress in reducing environmental impacts will be needed, however, to meet the challenges of the future posed by growth in aviation and the need to reduce emissions beyond current levels, particularly with respect to climate emissions.

It is clear that aviation emissions' impacts on health and the global climate will drive the FAA's research program in the future. These impacts are continually interpreted through regulatory and policy mandates, such as the Clean Air Act, the National Environmental Policy Act, FAA's NextGen program, and ICAO requirements, which in turn set new levels of performance that must be achieved. Those mandates are evaluated using the Five-Pillar Environmental Approach to define research plans and objectives as noted in Figure 8: Defining Research Initiatives.

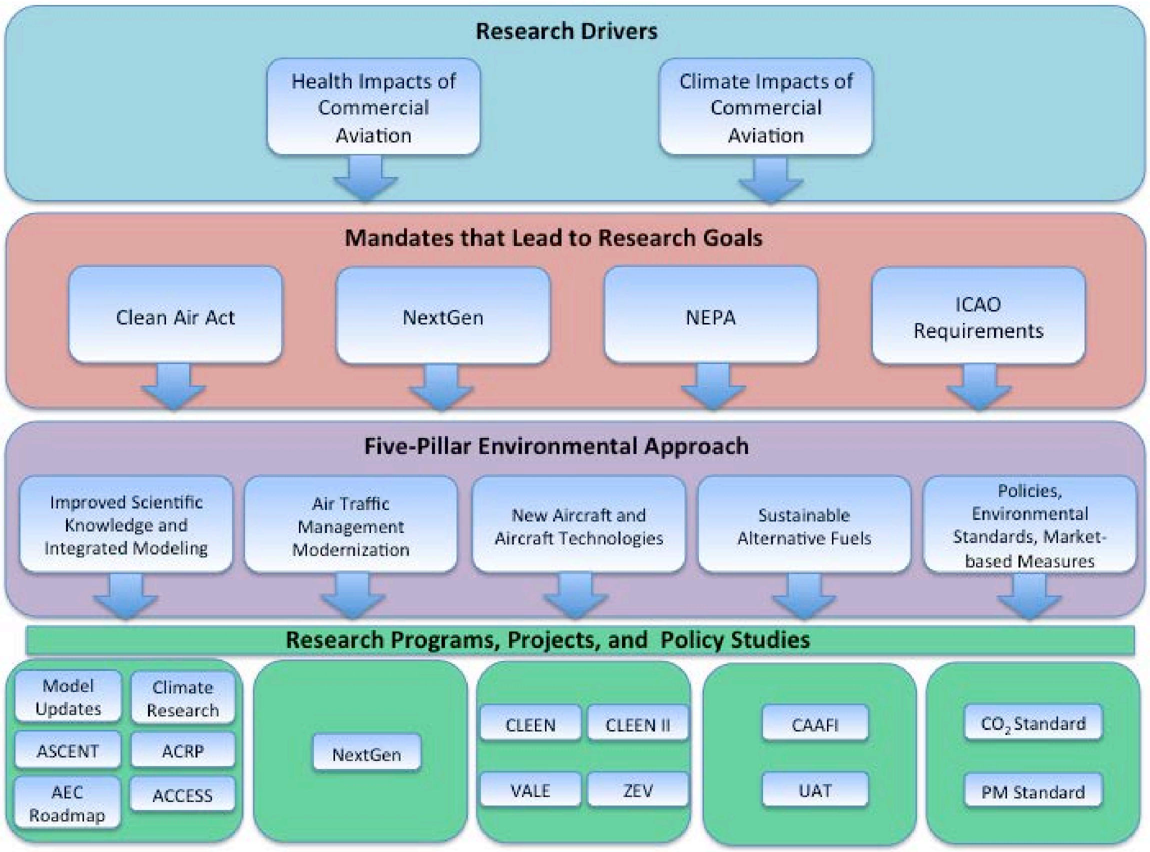

Figure 8: Defining Research Initiatives

FAA has set ambitious goals for the future. As expressed in the Aviation Environmental and Energy Policy Statement,[99] FAA's air quality goal is to achieve an absolute reduction of significant health and welfare impacts attributable to aviation, notwithstanding aviation growth. The Agency's climate goal is to limit the impact of aircraft CO_2 emissions on the global climate by achieving carbon neutral growth by 2020 compared to 2005 (i.e., zero growth in CO_2 emissions) and to achieve a net reduction of the climate impact from all aviation emissions by 2050. The energy efficiency goal of the US is to achieve at least 1 percent per year improvement in the energy efficiency of the National Airspace System. The FAA also recognizes ICAO's aspirational energy goals for international aviation as 2 percent improvement per year. Taken together, these goals represent a significant improvement in aviation's environmental performance but will take an ambitious R&D program to accomplish.

Planning is underway for CLEEN II with new, demanding goals for new technologies, new aircraft designs, new system designs, and new alternative fuels. New emissions measurement projects such as ACCESS in concert with NASA and collaborations with the international community developing particulate matter and CO_2 engine emission standards are envisioned. Emissions models must be have their dispersion modeling capabilities upgraded to meet the more demanding information required to fully understand health risks. FAA desires a better understanding of the interdependencies of emissions and noise and their interrelated impacts. And much more information is needed to understand the climate impacts of non-CO_2 aviation emissions.

The FAA cannot achieve these ambitious goals alone. Continued cooperation with other Federal agencies such as NASA, EPA, DOD, DOE, and USDA, as well as collaboration with corporations and industry associations, and the scientific community will be essential.

Achieving research goals will allow the aviation industry to significantly reduce its environmental impacts and begin to reduce its total emissions of PM, NO_x, and CO_2. This takes time, however. As noted earlier it takes 20 years for 86% of the fleet to achieve current new technology performance. This also assumes that funding will be available to continue current projects and to support new projects as planned.

The FAA Modernization and Reform Act of 2012 (FAA Reauthorization)[100] stipulated that an independent, outside panel of experts review energy-related and environment-related research programs. The review was conducted during the summer of 2013[101] to determine whether the programs (1) have well-defined, prioritized, and appropriate research objectives; (2) are properly coordinated with research programs at NASA, National Oceanic and Atmospheric Administration (NOAA), and other relevant agencies; (3) have allocated appropriate resources to the research objectives; and (4) have mechanisms for transitioning the results into FAA's broader activities.

The independent panel review found that FAA's research is well defined, effectively prioritized, and has relevant objectives. They also found the research is well coordinated with other agencies and significant efforts have been made to transition research to other parts of FAA. However, "***funding is, and will continue to be, a major constraint on the ability of the FAA to achieve its energy and environmental goals***." They further stated that, at current levels of funding, the programs have allocated appropriate resources to achieve research objectives yet given potential reductions in future funding levels, the achievement of research goals may be put in jeopardy. Further federal investment in aviation research and technology development will be essential to meet the government's commitment.

Conclusion

Aviation is a complex and vital industry serving not only the U.S. but also the entire world. It supplies tremendous economic benefits to those countries that embrace it. Its speed and accessibility are well suited to modern society as globalization, technology development, and just-in-time manufacturing transform the world. To maintain its central transportation role, aviation must ensure it can mitigate any environmental constraints that result from its operations.

There are features that distinguish aviation from other transportation modes and industries that must be factored into environmentally-motivated strategies. Aviation places a high premium on safety, which demands the incorporation of only proven and technically sound technologies to reduce environmental impacts. Aircraft are high cost and have a long life span, requiring long lead times for new technologies to be widely incorporated in the fleet. Airframe and engine manufacturers as well as airlines will need to invest the capital to build and operate aircraft with new technologies for aviation to realize the environmental and operational benefits. Airport infrastructure requires substantial planning and construction effort, as well as public and financial support. Such considerations increase the challenge of achieving the ambitious environmental and energy performance expectations envisioned in the NextGen transformation of the U.S. aviation system.

Within this framework of constraints, aviation has safely and progressively improved its environmental performance. This commitment to operating in balance with the environment and in support of beneficial environmental mitigation practices are forcefully stated in the FAA's Aviation Environmental and Energy Policy Statement, as further advanced by the Aviation Greenhouse Gas Emissions Reduction Plan[102]. Fuel economy, which is one strong indicator of environmental performance, has consistently improved. Aircraft engines have gotten more efficient and been designed with environmental performance in mind. Regulatory frameworks have developed to constrain emissions growth from many aviation sources. Improvements to the efficient operation of the complex aviation network have had a positive effect on the environment. And new fuels are being developed to reduce harmful emissions as well as aviation's impact on climate change. Much of this progress is a direct result of the research conducted in the programs planned and managed by FAA's Office of Environment and Energy.

FAA, together with EPA and NASA, is committed to ensuring aviation emissions do not pose human health risks, degrade the global climate, or restrain aviation's mobility and economic benefits enjoyed by society. Its consistent, coordinated effort and continuing success in technology research and development will ensure NextGen's goals can be met and environmental goals can be achieved. And the broad inclusion and sustained commitment to working with all stakeholders will ensure the U.S. will be a global leader in researching, developing, and implementing technological, operational, and policy initiatives that address both aviation's growth opportunities and environmental challenges.

Looking to the future, FAA has the strategic framework in place for planning and implementing an emissions research roadmap for continuing to mitigate the environmental impacts of aviation emissions. This includes continuing to improve understanding of the role of aviation emissions on health impacts on the surface of the Earth as well as climate change. FAA is working with industry and other stakeholders to advance the performance of the national and international aviation system as well as to improve individual system components. For example within ICAO, the FAA continues to work on a comprehensive basket of solutions to mitigate aviation noise and emissions impacts while simultaneously working to improve energy efficiency and security. The U.S. is committed to pursuing development of a global MBM for international aviation through ICAO. The global MBM is considered gap filler in the basket of measures that includes improvements in technology, operations and sustainable alternative fuels to achieve carbon neutrality for the world-wide aviation industry.

Abbreviations & Acronyms

ACCESS – Alternative Fuel Effects on Contrails and Cruise Emissions

ACCRI – Aviation Climate Change Research Initiative

ACRP – Airport Cooperative Research Program

AEC – Aviation Emissions Characterization Roadmap

AEE – Office of Environment and Energy

AIP – Airport Improvement Program

APEX – Aircraft Particle Emissions Experiment

APU – Auxiliary Power Unit

ASCENT – Aviation Sustainability Center

ASTM – American Society for Testing and Materials

BC – black carbon

BTU – British Thermal Unit

CAA – Clean Air Act

CAAFI – Commercial Aviation Alternative Fuels Initiative

CAEP – Committee on Aviation Environmental Protection

CCR – Climate Change Research

CDC – Centers for Disease Control and Prevention

CH_4 – methane

CLEEN – Continuous Lower Energy, Emissions, and Noise

CO – carbon monoxide

CO_2 – carbon dioxide

COE – Center of Excellence

EMS – Environmental Management System

EPA – Environmental Protection Agency

FAA – Federal Aviation Administration

GDP – gross domestic product

GSE – ground support equipment

HAP – hazardous air pollutant

HC – hydrocarbon

HNO_3 – nitric acid

H_2O – water

H_2SO_4 – sulfuric acid

ICAO – International Civil Aviation Organization

LTO – Landing Take Off

MBM – Market-Based Measure

N_2 – nitrogen

NAAQS – National Ambient Air Quality Standards

NASA – National Aeronautics and Space Administration

NEPA – National Environmental Policy Act

NextGen – Next Generation Air Transportation System

NH_3 – ammonia

NH_4NO_3 – ammonium nitrate

$(NH_4)_2SO_4$ – ammonium sulfate

N_2O – nitrous oxide

NOAA – National Oceanic and Atmospheric Administration

NO_2 – Nitrogen dioxide

NO_x – nitrogen oxides

O_2 – oxygen

O_3 – ozone

OPD – Optimized Profile Descents

PARTNER – Partnership for AiR Transportation Noise and Emissions Reduction

Pb – lead

PFC – Passenger Facility Charges

PM – particulate matter

$PM_{2.5}$ – particulate matter 2.5 microns and smaller

R&D – research and development

RNAV – area navigation

RNP – required navigation performance

S – sulfur

SO_2 – sulfur dioxide

SO_x – sulfur oxides

TRB – Transportation Research Board

UHC – unburned hydrocarbons

UAT – United Avgas Transition Plan

VALE – Voluntary Airport Low Emission Program

VOC – volatile organic compound

ZEV – Zero Emission Airport Vehicle and Infrastructure Pilot Program

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