

Models for Aircraft Surface Operations Environmental Analysis

Gregory D. Sweriduk* and Victor H. L. Cheng†
Optimal Synthesis Inc., Los Altos, CA 94022

David C. Foyle‡
NASA Ames Research Center, Moffett Field, CA 94035

Aircraft emissions at airports represent a significant environmental impact. Higher air quality standards have led to improvements in emissions over the past several decades, but future growth in air travel will make it more difficult to meet the standards. As part of current research into ways to improve airport surface operations, it was found that improved methods of estimating aircraft emissions on the surface were needed. The standard emissions analysis tool used in many studies is intended to capture the larger-scale trends and provides only a basic method of estimating emissions. New methods have been developed that take into account the dynamic behavior as aircraft maneuver around an airport and thus capture the smaller-scale variations. These models can provide more accurate estimates of emissions, at the expense of more detailed aircraft models.

Nomenclature

NO_x	=	oxides of nitrogen
CO	=	carbon monoxide
CO_2	=	carbon dioxide
UHC	=	unburned hydrocarbons
$PM_{2.5}$	=	Particulate Matter, size < 2.5 micrometers
PM_{10}	=	Particulate Matter, size < 10 micrometers
SN	=	Smoke Number
VOC	=	Volatile Organic Compounds

I. Introduction

AIR quality in the vicinity of airports has been a concern for a long time. Since the passage of the Clean Air Act in the U.S. in 1970, the Environmental Protection Agency (EPA) and the Federal Aviation Administration (FAA) have enacted regulations resulting in new engine designs that have substantially reduced aircraft emissions overall. Projections for the the future of air travel indicate continued growth, however. A substantial part of the research for the FAA's Next Generation Air Transportation System (NextGen) involves enabling higher-density operations at airports and clusters of airports around cities (metroplexes).¹ With the higher-density operations expected, the problem of air pollution at airports can be expected to get worse in the foreseeable future.

On the surface, aircraft engines spend most of the time at or near idle, the operating point at which the engine is least efficient and where the greatest concentrations of certain species of pollutants are produced. A comparison of two turbofan engines of different vintages in the same thrust category, the JT8D-7 and the CF34-10E6, shows that while the fuel consumption and most emissions indices have been reduced substantially at higher power settings, the values at the lowest power settings—where surface operations take place—have not changed much at all, despite the fact that these two engines were designed three decades apart.^{2,3}

Further advances in engine technology may reduce emissions further, but due to the long life cycle of transport aircraft, it can take many years before the majority of aircraft in the fleet will be equipped with any new technology

* Research Scientist, 95 First Street, Suite 240, AIAA Senior Member.

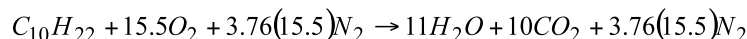
† Principal Scientist, 95 First Street, Suite 240, AIAA Associate Fellow.

‡ Research Psychologist, Human Systems Integration Division, MS 262-4.

so that the potential benefits may be fully realized. The most likely means for reducing emissions on the surface then, as well as the easiest to effect, will be changes in the way that aircraft are operated on the surface. In order to assess the impact of changes in surface operations on emissions, a method of estimating emissions with sufficient detail is needed. The currently available tools, as will be explained in Section III, do not include sufficient detail for this purpose. The present research is investigating ways of combining existing models to allow more accurate assessments. Section II will provide a brief description of aircraft emissions, Section III will discuss the different models, and Section IV will show some comparisons of the estimates produced by the different models.

II. Aircraft Emissions

Jet fuels are very similar to kerosene or No. 2 distillate oil, and can be reasonably represented by N-decane, $C_{10}H_{22}$.⁴ The balanced chemical reaction where all oxygen and fuel are burned and do not remain in the products (stoichiometric ratio) is⁴:



This is the ideal case, and in reality the process is not so simple and results in other by-products. Table 1 lists the main components of jet engine exhaust and their sources, and details of their formation are explained in the following sub-sections.

Table 1. Gas Turbine Exhaust Products⁶

Major Species	Typical Concentration (% Volume)	Source
Nitrogen (N ₂)	66 – 72	Inlet Air
Oxygen (O ₂)	12 – 18	Inlet Air
Carbon Dioxide (CO ₂)	1 – 5	Oxidation of Fuel Carbon
Water Vapor (H ₂ O)	1 – 5	Oxidation of Fuel Hydrogen
Minor Species Pollutants	Typical Concentration (PPMV)	Source
Nitric Oxide (NO)	20 – 220	Oxidation of Atmosphere Nitrogen
Nitrogen Dioxide (NO ₂)	2 – 20	Oxidation of Fuel-Bound Organic Nitrogen
Carbon Monoxide (CO)	5 – 330	Incomplete Oxidation of Fuel Carbon
Sulfur Dioxide (SO ₂)	Trace – 100	Oxidation of Fuel-Bound Organic Sulfur
Sulfur Trioxide (SO ₃)	Trace – 4	Oxidation of Fuel-Bound Organic Sulfur
Unburned Hydrocarbons (UHC)	5 – 300	Incomplete Oxidation of Fuel or Intermediates
Particulate Matter Smoke	Trace – 25	Inlet Ingestion, Fuel Ash, Hot-Gas-Path Attrition, Incomplete Oxidation of Fuel or Intermediates

In the literature, the three main pollutants evaluated are carbon monoxide (CO), oxides of nitrogen (NO_x), and unburned hydrocarbons (UHC). In 1981, ICAO (International Civil Aviation Organization) first adopted standards relating to the control of smoke and gaseous emissions (UHC, CO, and NO_x) from turbojet and turbofan engines intended for subsonic and supersonic propulsion.⁵ Figure 1 shows the general behavior of the formation of these components as a function of the throttle. It can be seen that the concentrations of these different pollutants depends on the flame temperature, which is a function of the throttle setting, and there is not a clear-cut minimum point.

Other pollutants include particulate matter (PM), whose effects on health and climate have only recently begun to be understood and for which few standards exist; a related metric is smoke number (SN). Carbon dioxide (CO₂)

historically has been considered a harmless by-product of combustion along with water vapor and has only recently come to be considered a pollutant. Each of these will be discussed in the following sections.

A. Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless, poisonous gas formed when carbon in fuels is not burned completely.⁷ According to Ref. 6, CO emissions from a typical gas turbine combustion system are less than 10 ppmvd (parts per million by volume dry) at all but very low loads for steady-state operation, but during ignition and acceleration, transient emission levels may be higher. As firing temperature is reduced below about 1500°F/816°C, the carbon monoxide emissions increase quickly.⁶

Carbon monoxide enters the bloodstream and reduces oxygen delivery to the body's organs and tissues. The health threat from CO is most serious for individuals with cardiovascular disease. Healthy individuals are also affected, but only at higher levels of exposure. Effects of exposure to elevated CO levels include: visual impairment, reduced work capacity, reduced manual dexterity, poor learning ability, and difficulty in performing complex tasks. EPA's health-based national air quality standard for CO is 9 parts per million (ppm) (averaged over 8 hours).⁷

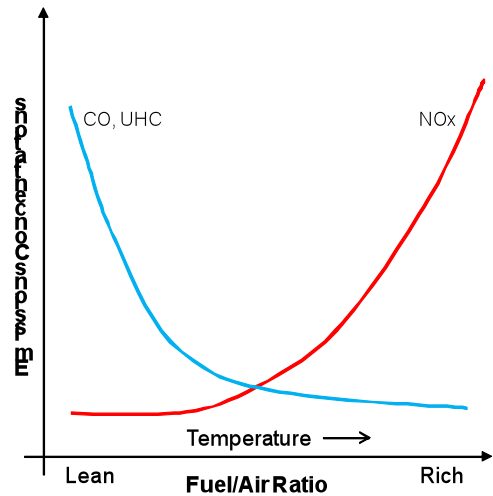


Figure 1. Major Pollutant Concentrations as a Function of Throttle

B. Nitrogen Oxides

The following discussion of NO_x formation follows largely from Ref. 6. In the early 1970s when emission controls were originally introduced, the primary regulated gas turbine emission was NO_x. Nitrogen oxides (NO_x = NO + NO₂) can be divided into two classes according to their source: thermal NO_x and organic NO_x. Nitrogen oxides can form from the oxidation of the free nitrogen in the combustion air or the fuel and are called "thermal NO_x." They are mainly a function of the stoichiometric adiabatic flame temperature of the fuel, the temperature reached by burning a theoretically correct mixture of fuel and air in an insulated vessel. The following is the relationship between combustor operating conditions and thermal NO_x production:

- NO_x increases strongly with fuel-to-air ratio or with firing temperature
- NO_x increases exponentially with combustor inlet air temperature
- NO_x increases with the square root of the combustor inlet pressure
- NO_x increases with increasing residence time in the flame zone
- NO_x decreases exponentially with increasing water or steam injection or increasing specific humidity

"Organic NO_x" results from the oxidation of nitrogen bound in the fuel (fuel-bound nitrogen (FBN)), which is generally small in jet fuels. Only very small amounts of the available free nitrogen (almost all from air) are oxidized to form nitrogen oxide, but the oxidation of FBN to NO_x is almost complete. Typically the efficiency of conversion of FBN into nitrogen oxide is 100% at low FBN contents, but at higher levels, the conversion efficiency decreases. Organic NO_x formation is less well understood than thermal NO_x formation, but formation is also affected by turbine firing temperature.

NO_x is a key component in the formation of smog and also acid rain (SO₂ can also form acid rain). Nitrogen oxides are important in forming ozone and may affect both terrestrial and aquatic ecosystems. Nitrogen oxides in the air are a potentially significant contributor to a number of environmental effects such as acid rain and eutrophication in coastal waters like the Chesapeake Bay. Eutrophication occurs when a body of water suffers an increase in nutrients that reduce the amount of oxygen in the water, producing an environment that is destructive to fish and other animal life.⁷

Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infections such as influenza. The effects of short-term exposure are still unclear, but continued or frequent exposure to concentrations that are typically much higher than those normally found in the ambient air may cause increased incidence of acute respiratory illness in children. EPA's health-based national air quality standard for NO₂ is 0.053 ppm (measured as an annual average).⁷

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C. Unburned Hydrocarbons

Unburned hydrocarbons (UHC) are associated with combustion inefficiency.⁶ UHC is another key component in the formation of smog. Volatile organic compounds (VOC) such as toluene and various forms of benzene make up a significant portion of UHC.⁵ VOC are known to have adverse health effects, some being carcinogenic. In general, long-term exposure to low concentrations of VOC in water or air, at or above regulatory standards—such as Maximum Contaminant Levels—may result in liver or kidney effects.^{8,9} The UHC emissions from heavy-duty gas turbine combustors show the same type of hyperbolic function of combustion temperature as carbon monoxide.⁶

D. Carbon Dioxide

Carbon dioxide is a colorless, odorless gas that is a normal by-product of the combustion of fossil fuels. CO₂ in low concentrations is not in itself harmful to humans, but its links to climate change have made it a cause for serious concern. In addition to links to global warming, increased levels of CO₂ in the atmosphere leads to the acidification of bodies of water, which can have detrimental effects on their ecosystem; e.g., Ref. 10. In terms of potential health problems, higher levels have been associated with headaches, sleepiness, poor concentration, loss of attention, increased heart rate and slight nausea.¹¹ Indoor air quality standards vary between 1,000 ppm and 5,000 ppm.

E. Particulate Matter

Combustion of fuels produces particle emissions that consist of a mixture of microscopic solids, liquid droplets, and particles with solid and liquid components, suspended in the air.¹² The particles are made up of various components, including black carbon (soot), inorganic acids and their salts, organic chemicals, plus whatever naturally-occurring particles such as dust are present in the ambient air. Volatile particles can evaporate, while non-volatile particles, such as soot, remain in a condensed state. The size of the particles is important since smaller particles can be inhaled more deeply into the lungs, and thus have the potential for more significant health impact compared to larger particles. The size also affects the residence time in the air. Particles smaller than 10 μm but larger than about 2.5 μm are referred to as “coarse” particles and typically represent most of the mass included in PM₁₀, the mass of particles smaller than 10 μm.¹² “Fine” particles are those between 2.5 μm and 0.1 μm in size, and are referred to as PM_{2.5}, meaning all particles less than 2.5 μm. Ultrafine particles can actually accumulate to form larger ones. In fact, many of the particulate forms that have adverse effects are not formed directly in the engine and instead form in the exhaust stream after it has left the engine.

Smaller particles are more likely to enter the respiratory system. Studies have indicated a significant association between exposure to fine and ultrafine particles and increased risk of heart and lung diseases such as cardiac arrhythmias, heart attacks, respiratory symptoms, asthma attacks, and bronchitis, and they can aggravate existing heart and lung conditions.¹² The effects on the climate are still not certain, but there is some evidence that particles have a contribution.¹³

The EPA establishes the National Ambient Air Quality Standards (NAAQS), which limit the concentration of select pollutants in the outside air.¹² The Clean Air Act requires the EPA to set the NAAQS at levels that protect (1) the public health with an adequate margin of safety (the primary NAAQS), and (2) the public welfare from any known or anticipated adverse effects (the secondary NAAQS). Particulate matter is one of the criteria pollutants regulated through the NAAQS. There are currently no standards for aircraft engines in regard to particulate matter – only smoke number (SN) is currently regulated.¹⁴

The production of soot in gas turbines is a complex process that is still not well understood.¹⁵ The ICAO aircraft engine database (the basis of EDMS) does not give particulate information but does include data on the smoke number. SN can vary a great deal with the throttle setting, and between different engine makes and models.¹⁵ Some studies have developed estimates of soot concentration as a function of SN. However, there is no direct connection between the two. The connection depends on the soot properties, especially the particle size distribution, of a given engine. A rough approximation was presented in Ref. 14, and measurement data for some types of aircraft were given in Ref. 16. The Department of Transportation has produced some empirical formulas to estimate PM with an EI similar to the ICAO database.¹⁷

III. Emissions Models

Various possibilities for modeling emissions for surface operations were investigated. In the following subsections, three types of models will be described: the constant-rate model, computational models, and dynamic look-up models.

A. Constant-rate

The constant-rate model is used in the Emissions and Dispersion Modeling System (EDMS). The EDMS was identified by the FAA in 1998 as the required model to perform air quality analyses for aviation sources.¹⁸ EDMS models aircraft activity with 6 modes of operation corresponding to the following portions of Landing-Takeoff (LTO) cycle: Approach, Taxi-In, Gate (main engine startup), Taxi-Out, Takeoff, and Climbout. The EDMS uses emissions information from the ICAO Exhaust Emissions Databank. An example of the data provided is shown in Table 2.

Table 2. Example of ICAO Engine Emissions Data²

Phase	Power Setting (% max. Thrust)	Fuel Flow (kg/s)	Emissions Index (g/kg)			Smoke Number
			UHC	CO	NO _x	
Idle	7	0.1323	3.12	14.14	2.9	–
Approach	30	0.2977	0.6	2.14	6.0	–
Climb-out	85	0.18	0.18	1.11	14.5	–
Take-off	100	1.04	0.15	1.04	19.3	10.1

The EDMS estimates emissions based on operating mode. It uses a fixed throttle setting for each mode and multiplies the corresponding fuel flow rate by the time spent in that mode to get the mass of fuel burned. The Emissions Index (EI) for each species is multiplied by the fuel mass to obtain the total mass of that species. On the surface, though, the throttle is not constant. The throttle can often be set to idle once the desired taxi speed has been reached, but this will depend on weight, grade, etc. However, the pilot has to speed up and slow down for turns and other traffic. The “Idle” setting listed in the tables is actually is slightly higher than the true idle, so it represents in some sense an average value. In order to obtain a more precise estimate of emissions, other models were sought.

The ICAO database does not include information on CO₂. The EPA has determined a conversion factor for CO₂ per gallon of diesel fuel, which is very similar to jet fuel, so the values for diesel fuel may be used in the absence of a more detailed model. The conversion factor is 22.2 pounds mass per gallon, or approximately 3.3248 pounds per pound of diesel¹⁹ (density of jet fuel \approx 0.8 g/ml = 6.6771 lbm/gal [Ref. 20]). The ICAO database also does not include information on particulate matter. Fortunately, recent work at the Department of Transportation has produced some empirical formulas that will allow a reasonable estimate of PM.¹⁷

B. Computational

In lieu of more detailed emissions data, another way to obtain estimates is to use a detailed engine model and compute the emissions from the model state variables. Examples of such models include C-MAPSS and C-MAPSS40K developed by NASA Glenn Research Center.²¹ These are component-level models that include thermodynamic states in the engine. There are also engine design and analysis programs that can be used to develop dynamic engine models as well. Some approximations for engine parameters can be obtained from engine design textbooks such as Refs. 4, 22, 23, and 24. Semi-empirical formulas for computing the emissions can be found in Refs. 15, 22, and 25–27. The main drawback of this method is that such engine models are not readily available for a variety of engines, and developing one takes some time and expertise.

C. Dynamic Look-up

In between the two previous kinds of models is a table look-up method using the ICAO emissions databank together with the output of a dynamic engine model. The ICAO tables include both thrust and fuel flow rate so either of these can be used as the independent variable. The thrust or fuel flow can be the output of a simplified engine model. Various aircraft simulations have dynamic engine models that may be used for this purpose. There are different techniques for performing the interpolation as well. There are the standard techniques such as linear, cubic, spline, etc., but the method used here is one developed by the Boeing Company²⁸ that uses piecewise linear fits on a logarithmic scale and is illustrated in Figure 2. The resulting estimates of emissions are dynamic, but do not require a detailed engine model. The accuracy depends on the number of points in the table, and as seen in Table 2 the number of points in ICAO tables is very limited. This approach will capture the effects of variations in throttle, but will not capture the transient behavior of the combustion process that can affect the emissions on a smaller time scale.

IV. Results

In the first example, a simple trajectory with different final times was used for comparison. Each trajectory consisted of an initial acceleration, a coasting phase, and a deceleration. The total distance covered in each case was 1000 ft. The simulation used was NASA Langley’s Transport System Research Vehicle (TSRV), a 6-DOF model of a Boeing 737-100 with landing gear dynamics (including brakes and rolling resistance) and a medium-fidelity model of the engine dynamics[§]. The total masses for the various pollutants using two emissions models are shown in Table 3 for each of the trajectories, and fuel consumption values are shown in Table 4. In the shortest-time case, the EDMS method produces a smaller value of CO₂, probably a result of the lower average value of thrust—the short duration requires higher acceleration and thus a higher average value of thrust for the dynamic model. In the longest-time case, the EDMS value is slightly higher, likely because the average thrust value is lower than that assumed by EDMS.

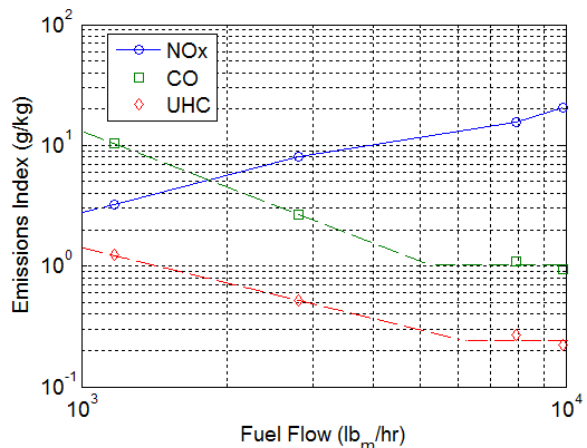


Figure 2. Boeing Interpolation Method

Table 3. Masses of Emissions for Trajectories of Varying Duration, in grams

Species	Method	Duration		
		40 s	50 s	60 s
NO _x	Dynamic Look-up	50.61	42.62	44.74
	Constant-Rate	37.63	47.04	56.45
CO	Dynamic Look-up	120.15	161.62	200.16
	Constant-Rate	123.01	153.76	184.51
UHC	Dynamic Look-up	14.70	18.37	22.04
	Constant-Rate	14.70	18.38	22.05
CO ₂	Dynamic Look-up	95.79	100.94	113.74
	Constant-Rate	86.21	107.76	129.32
PM	Dynamic Look-up	88.10	92.73	104.45
	Constant-Rate	79.24	99.04	118.85

Table 4. Fuel Consumption for Trajectories, in lbm

Method	Duration		
	40 s	50 s	60 s
Dynamic Look-up	28.81	30.36	34.21
Constant-Rate	25.93	32.41	38.89

The following example is an actual taxi route at Dallas-Fort Worth International Airport obtained from SMS (Surface Management System) data²⁹ (Figure 3). The results of the emissions and fuel estimates are shown in Table 5 and Table 6. Again, except for UHC there are significant differences in the estimates obtained with the two models.

[§]Pratt & Whitney JT8D-17 turbofans. Although the aircraft type (-100) would imply a -7 or -9 engine type, the thrust and fuel flow produced by the engine model was more consistent with the -17 engine type; so the emissions table for this type was used.

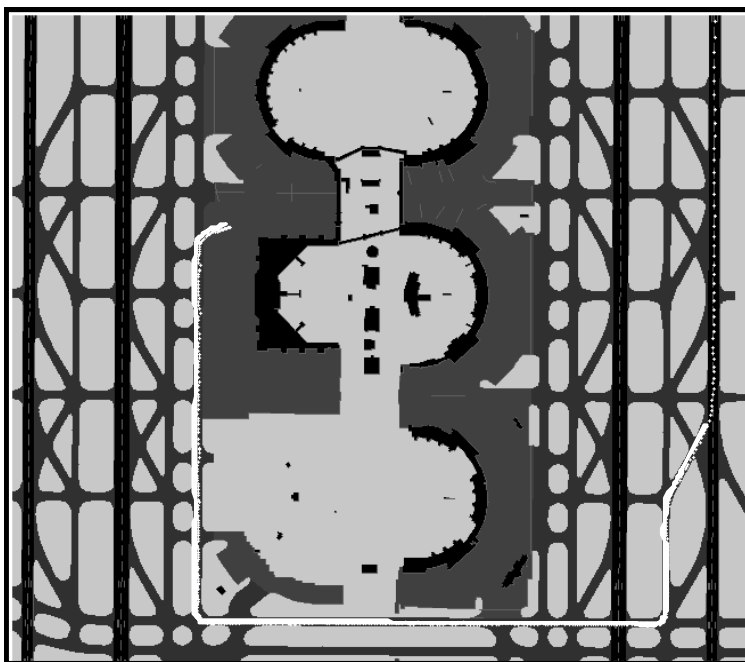


Figure 3. Example Taxi Route

Table 5. Emissions for Sample Trajectory (in grams)

Method	Pollutant				total
	NO _x	CO	UHC	PM	
Dynamic Look-up	2.8713e+002	1.5585e+003	1.6639e+002	7.3526e+002	2.7472e+003
Constant-Rate	4.2618e+002	1.3931e+003	1.6648e+002	8.9734e+002	2.8831e+003

Table 6. Fuel Consumption and Carbon Dioxide for Trajectories (in lbm)

Method	Fuel	CO ₂
Dynamic Look-up	240.9	8.0118e+002
Constant-Rate	293.65	9.7634e+002

V. Conclusion

Alternative methods for estimating aircraft emissions during surface operations were presented. The results from the inclusion of throttle variations differ markedly from the standard model which assumes a fixed throttle setting. The standard model assumes a throttle value higher than idle, but during taxi operations, much of the time the engines are at idle. More research is necessary to validate the model. Recent evidence from other sources suggests that the emissions at idle can be substantially different from the ICAO value, and can also depend on the ambient temperature and the amount of bleed air being used to power on-board systems such as the cabin ventilation system. The dynamic engine model used was specific to one engine type, so it is not readily applicable to any aircraft, but it provided the higher fidelity necessary to assess the importance of including thrust variations.

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References

- ¹Anon., "Concept of Operations for the Next Generation Air Transportation System," v. 3.2, Joint Planning and Development Office, Washington, DC, September 30, 2010, URL: http://jpe.jpdo.gov/ee/docs/conops/NextGen_ConOps_v3_2.pdf.
- ²"ICAO Engine Exhaust Emissions Databank, JT8D-7," URL: http://www.caa.co.uk/docs/702/1PW007_01102004.pdf.
- ³"ICAO Engine Exhaust Emissions Databank, CF34-10E6," URL: http://www.caa.co.uk/docs/702/8GE116_04102007.pdf.
- ⁴Flack, R. D., *Fundamentals of Jet Propulsion with Applications*, Cambridge, U.K., 2005.
- ⁵Herndon, S. C., Rogers, T., Dunlea, E. J., Jayne, J. T., Miake-Lye, R., and Knighton, B., "Hydrocarbon Emissions from In-Use Commercial Aircraft during Airport Operations," *Environmental Science and Technology*, Vol. 40, N. 14, 2006.
- ⁶Pavri, R. and Moore, G. D., "Gas Turbine Emissions and Control," GE Power Systems, GER-4211, Atlanta, GA, March, 2001.
- ⁷"Health Effects of Pollution," U. S. Environmental Protection Agency, Region 7 (<http://www.epa.gov/Region7/programs/artd/air/quality/health.htm>).
- ⁸"Environmental and Workplace Health," Health Canada, Ottawa, Ontario, Canada, URL: http://www.hc-sc.gc.ca/ewh-semt/air/out-ext/effe/talk-a_propos-eng.php.
- ⁹"Volatile Organic Compounds Health Effects Fact Sheet," Colorado Department of Public Health and Environment, Denver, CO, November 2000, URL: <http://www.cdphe.state.co.us/hm/schlage/vocfactsheet.pdf>.
- ¹⁰"Ocean Acidification Could Have Broad Effects On Marine Ecosystems," *ScienceDaily*, Dec. 18, 2008.
- ¹¹"Chemical Fact Sheet – Carbon Dioxide," Wisconsin Department of Health Services, Madison, WI, URL: <http://dhs.wisconsin.gov/eh/chemfs/fs/CarbonDioxide.htm>.
- ¹²"Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data," Airport Cooperative Research Program Report 9, Transportation Research Board of the National Academies, Washington, DC, 2008.
- ¹³"Global Dimming," Wikipedia, URL: http://en.wikipedia.org/wiki/Global_dimming.
- ¹⁴Pehrson, J., "Aircraft Particulate Matter Emissions," *Transportation Research Board 84th Annual Meeting*, January 12, 2005.
- ¹⁵Doppelheuer, A., and Lecht, M. "Influence of Engine Performance and Emission Characteristics," *RTO AVT Symposium on Gas Turbine Engine Combustion, Emissions, and Alternative Fuels*, Lisbon, Portugal, Oct. 12–16, 1998.
- ¹⁶Mazaheri, M., Johnson, G. R., and Morawska, L., "Particle and Gaseous Emissions from Commercial Aircraft at Each Stage of the Landing and Takeoff Cycle," *Environmental Science and Technology*, Vol. 43, N. 2, 2009.
- ¹⁷Wayson, R. L., Fleming, G. G., and Iovinelli, R., "Methodology to Estimate Particulate Matter Emissions from Certified Commercial Aircraft Engines," *Journal of the Air & Waste Management Association*, Vol. 59, No. 1, 2009, pp. 91–100.
- ¹⁸"Emissions and Dispersion Modeling System (EDMS) Version 5 Technical Manual," FAA-AEE-07-07 (Rev. 1 – 04/08/09), CSSI, Inc., Washington, DC, 2009.
- ¹⁹"Emissions Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel," EPA420-F-05-001, February, 2005, URL: <http://www.epa.gov/OMS/climate/420f05001.htm>.
- ²⁰"Material Safety Data Sheet: Aviation Turbine Fuel," MSDS 513, Rev. 19, Chevron Global Aviation, Houston, TX, April, 2003, URL: http://www.chevronglobalaviation.com/docs/aviation_turbine_fuel.doc.
- ²¹Frederick, D. K., DeCastro, J. A., and Litt, J. S., "User's Guide for the Commercial Modular Aero-Propulsion System Simulation (C-MAPSS)," NASA/TM-2007-215026, Glenn Research Center, Cleveland, OH, October, 2007.
- ²²Lefebvre, A. H., *Gas Turbine Combustion*, 2nd Ed., Taylor and Francis, 1999.
- ²³Oates, G. C. (ed.), *Aerothermodynamics of Aircraft Engine Components*, AIAA Education Series, AIAA, New York, NY, 1985.
- ²⁴Mattingly, J. D., Heiser, W. H., and Pratt, D. T., *Aircraft Engine Design, 2nd Ed.*, AIAA Education Series, AIAA, Reston, VA, 2002.
- ²⁵Rizk, N. K., and Mongia, H. C., "Semianalytical Correlations for NO_x, CO, and UHC Emissions," *Journal of Engineering for Gas Turbines and Power*, Vol. 115, July, 1993, pp. 612-619.
- ²⁶Rizk, N. K., and Mongia, H. C., "Emissions Predictions of Different Gas Turbine Combustors," AIAA Paper 94-0118, *32nd Aerospace Sciences Meeting and Exhibit*, Reno, NV, Jan. 10-13, 1994.
- ²⁷Valachovic, T. G., "Numerical Predictions of Idle Power Emissions from Gas Turbine Engines," ASME Paper 93-GT-175, *International Gas Turbine and Aeroengine Congress and Exposition*, Cincinnati, OH, May 24–27, 1993.
- ²⁸Baughcum, S. L., Tritz, T. G., Henderson, S. C., and Pickett, D. C., "Scheduled Civil Aircraft Emission Inventories for 1992: Database Development and Analysis," NASA Contractor Report 4700, NASA Langley Research Center, April, 1996.
- ²⁹SODAA User's Guide, Mosaic ATM, Inc., URL: http://sodaa.mosaicatm.com/sodaa_current/sodaasite/SODAA_User_Guide.pdf