Relationships Between Emissions-Related Aviation Regulations and Human Health

by

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Abstract

Inventories of aircraft emissions from the year 2005 were assessed. It was estimated that aircraft were responsible for 140 to 160 yearly incidences of premature mortality from exposure to ambient $PM_{2.5}$. Ammonium sulfate concentrations caused 46% to 69% of the incidences, while ammonium nitrate caused 18% to 20%. Organics related volatile primary PM caused 6% - 18%, nonvolatile primary PM caused 5% - 14%, and sulfates-related volatile primary PM caused 0% to 4% of the incidences. A policy strategy that reduces fuel sulfur content to 15 ppm would reduce incidences by 38% and may be cost-beneficial.

Introduction

Commercial aviation allows the rapid transport of people and goods globally and generates jobs worldwide. This includes the activities of aircraft, ground support equipment, and transport to and from airports. The aviation industry contributes 5.4% of GDP (approximately $640 billion) in the United States and is also a strong contributor to U.S. exports (Joint Planning and Development Office 2007). Aviation activity is also a source of air emissions, and some emissions have negative impacts on the environment and human health through impacts on local and regional air quality (Ratliff, Sequeira, Waitz, et al. 2008). Specifically, influences on ambient concentrations of tropospheric ozone and particulate matter below 2.5 μm in size ($PM_{2.5}$) are correlated with incidences of respiratory and cardiovascular illness as well as premature mortality (U.S. Environmental Protection Agency 2004b, U.S. Environmental Protection Agency 2006b). Because the U.S. demand for aviation may triple by 2025 (Joint Planning and Development Office 2007), potentially increasing aviation emissions, an understanding of aviation emissions, air quality impacts, health impacts, and relationships to aviation regulations is critical.

1. Background

Jet engines emit a range of chemicals during operation; approximately 70% of the total emitted mass is CO_2 and 30% is water (Federal Aviation Administration 2005). Less than 1% of the mass consists of carbon monoxide (CO), unburned hydrocarbons (HCs, which include volatile organic compounds or VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), PM, and trace compounds like metals (Kugele, Jelinek and Gaffal 2005). Aircraft emissions below 3000 feet are currently less than 1% each of total CO, NO_x, VOC, SO_2, and $PM_{2.5}$ emissions in the United States (U.S. Environmental Protection Agency 2007e).

Aircraft emissions are strongly influenced by emissions standards established by the International Civil Aviation Organization (ICAO) (International Civil Aviation Organization 2005, International Civil Aviation Organization 2007). Fuel standards set by ASTM International also play a critical role (ASTM International 2007). The fuel standards control the sulfur content of fuel, influencing sulfur-related emissions.

1.1. Aircraft emissions and related regulations

Jet aircraft emit CO and HCs because aviation fuel is hydrocarbon-based and undergoes incomplete combustion in the engine (Flagan and Seinfeld 1988, Kugele, Jelinek and Gaffal 2005, Yelvington, Herndon, Wormhoudt, et al. 2007). VOCs are hydrocarbon vapors, which influence ambient ozone concentrations through reactions with NO_x and sunlight as well as CO in some cases (U.S. Environmental Protection Agency 2006b). Ozone is not emitted directly by aircraft engines (Federal Aviation Administration 2005). CAEP standards allow engines with higher thrust ratings to emit more CO and HCs.

NO_x is produced by the high temperature combustion of fuels in the presence of air (Flagan and Seinfeld 1988). NO_x emissions influence ozone concentrations as well as concentrations of certain PM species (such as ammonium nitrate) (U.S. Environmental Protection Agency 2004a, U.S. Environmental Protection Agency 2006b). CAEP standards allow engines with higher pressure ratios and thrust ratings to emit more NO_x. The standards have been updated several times since their establishment in 1981, most recently at the fourth meeting of CAEP (CAEP/4) in 1999 and at CAEP/6 in 2005. The United States Environmental Protection Agency (EPA) has not promulgated the CAEP/6 standards (United States Code 2005).

SO_x is created when fuels containing sulfur are burned, and the emitted mass is strongly correlated with fuel sulfur content (Flagan and Seinfeld 1988). SO_x emissions influence ambient PM concentrations (such as ammonium sulfate particles) (U.S. Environmental Protection Agency

2004a). Increases in SO_x emissions can also reduce concentrations of ammonium nitrate, as ambient ammonium will preferentially bond with sulfates (Greco, Wilson, Spengler and Levy 2007). CAEP has not set a SO_x standard, but ASTM International has set a standard of 3000 parts per million (ppm) fuel sulfur content (ASTM International 2007, International Civil Aviation Organization 2005). Fuel sulfur content varies between 500 and 1000 ppm worldwide (Chevron Corporation 2006).

PM is a combination of species with different sizes and compositions and is classified as primary or secondary PM. Primary PM is created directly by combustion, abrasion, and erosion processes, while secondary PM is created by chemical reactions involving NO_x, SO_x, VOCs, ammonia, and other compounds in the atmosphere (Kugele, Jelinek and Gaffal 2005, U.S. Environmental Protection Agency 2004a). PM is also classified as nonvolatile or volatile; nonvolatile particles are not chemically reactive, while volatile particles are formed from gaseous precursors.

Aircraft primary PM is $PM_{2.5}$ and consists of nonvolatile particles of elemental carbon and volatile particles consisting of sulfates and organic carbons (related to the sulfur and hydrocarbons in fuel). Only nonvolatile primary PM is measurable directly at the engine exit; volatile particles are thus not technically primary PM but are included in EPA aircraft emissions inventories and often categorized as primary PM (CSSI Inc. 2007, U.S. Environmental Protection Agency 2007e). CAEP standards address aircraft PM emissions indirectly via the smoke number (SN) metric; higher smoke numbers are correlated with more visible exhaust plumes, and the CAEP SN standard mandates decreasing SN with increasing engine thrust rating.

1.2. Ambient pollutant concentrations and their health effects

Emissions influence ambient concentrations of pollutants through transport processes and chemical reactions (Ratliff, Sequeira, Waitz, et al. 2008); the ultimate health impacts of pollutants are related to population exposure (Greco, Wilson, Spengler and Levy 2007). Increases in ambient concentrations of $PM_{2.5}$ and ozone are correlated with increases in a variety of cardiovascular and respiratory diseases as well as premature mortality (U.S. Environmental

Protection Agency 2004b, U.S. Environmental Protection Agency 2006b); for example, a Harvard study of six cities as cited by (U.S. Environmental Protection Agency 2004b) found a 4% to 23% increase in statistical incidences of premature mortality for every 10 $\mu g/m^3$ increase in ambient $PM_{2.5}$ concentrations. The health effects of specific PM species are still being researched; studies such as (Greco, Wilson, Spengler and Levy 2007) and (Levy, Wilson, Evans and Spengler 2003) have assumed that each species has the same health damage per unit mass. Ozone concentrations are associated with respiratory illnesses, particularly asthma; associations with premature mortality have been observed but are less well understood.

Direct exposure to concentrations of NO_x, SO_x, CO, and VOCs are correlated with respiratory illness, but health effects occur mainly at concentrations higher than ambient levels, are poorly understood, or primarily affect populations with vulnerable respiratory systems (such as asthmatic children) (U.S. Environmental Protection Agency 1994a, U.S. Environmental Protection Agency 1994b, U.S. Environmental Protection Agency 2002, U.S. Environmental Protection Agency 2007d). These compounds are often considered to be more important as precursors to PM and ozone, and recent EPA rulemakings have considered PM- and ozone-related health effects specifically (U.S. Environmental Protection Agency 2004d, U.S. Environmental Protection Agency 2005b, U.S. Environmental Protection Agency 2006a, U.S. Environmental Protection Agency 2007a).

2. Methodology and analysis

This paper utilized data and methods applied in a study of how aircraft impact air quality in the United States. The study was mandated by the Energy Policy Act of 2005 (United States Statutes at Large 2005) and is described in detail in (Ratliff, Sequeira, Waitz, et al. 2008). It focused on health incidences due to aircraft-induced changes in ambient ozone and $PM_{2.5}$ concentrations. Additional methods were used in this paper to further analyze the study results and apportion health incidences to different species of PM.

2.1. Creation of inventories

The EPA 2001 National Emissions Inventory was used to obtain baseline emissions in the continental United States. Note that the 2001 NEI is an internal EPA inventory used for EPA's

Clean Air Interstate Rule regulatory impact analysis (U.S. Environmental Protection Agency 2005a). The year 2005 aircraft emissions from 325 airports in 273 counties were estimated using the Emissions and Dispersion Modeling System (EDMS) (CSSI Inc. 2007) and several sources of operational and aircraft specification data (BACK Aviation Solutions 2007, Bureau of Transportation Statistics 2008, Federal Aviation Administration 2007a, Federal Aviation Administration 2007b, Federal Aviation Administration 2008). EDMS generated emissions below 3000 feet, an assumption for the thickness of the earth's atmospheric boundary layer (where turbulent mixing occurs),

The primary PM estimation method used for the Energy Policy Act (EPAct) study is a modification of ICAO's First Order Approximation (FOA) version 3.0 known as FOA3a (Ratliff, Sequeira, Waitz, et al. 2008). FOA3a includes margins to conservatively accommodate uncertainties in the estimation of PM from aircraft. In comparison with FOA3, the application of FOA3a increased the masses of sulfate-, organic carbon-, and elemental carbon-related primary $PM_{2.5}$ emissions by factors of 10.2, 3.5, and 3.4, respectively. The fuel sulfur content was assumed to be 680 ppm for the emissions inventory, but the sulfur content for 78 airports was incorrectly specified as 400 ppm, leading to a 20% reduction in SO_x mass.

2.2. Air quality modeling

The impacts of aircraft emissions on $PM_{2.5}$ and ozone concentrations were modeled using the Community Multiscale Air Quality Model (CMAQ) (CMAS Center and Center for Environmental Modeling for Policy Development 2007) and guidance procedures described in (U.S. Environmental Protection Agency 2007c). CMAQ determined changes in concentrations of PM and associated particle-bound water. The water mass was included because epidemiology literature references EPA's ambient PM measurements, which include water mass (U.S. Environmental Protection Agency 2007c).

Table 1 shows changes in concentrations of total $PM_{2.5}$ (in $\mu g/m^3$) and ozone (in parts per billion, or ppb) across the continental U.S. due to aircraft emissions.

Table 1: Changes in $PM_{2.5}$ and ozone concentrations due to aircraft emissions

	With aircraft emissions	Without aircraft emissions	Percent Change
$PM_{2.5}$ ($\mu g/m^3$, annual national average)	12.60	12.59	-0.08%
Ozone (ppb, 8-hour national average)	84.95	84.85	-0.12%

The largest increase in $PM_{2.5}$ due to aircraft occurred in Riverside County, CA (0.52% increase from 28.73 to 28.88 $\mu g/m^3$), while the largest 8-hour ozone increase occurred near the Atlanta, GA area (0.31% increase from 96.0 to 96.3 ppb). Aircraft emissions caused ozone to decrease in 24 counties due to complex coupling between NO_x and VOCs; these occurrences are known as disbenefits. Ambient VOCs often come from biogenic sources (Kesselmeier and Staudt 1999), so VOC concentrations can be low in city centers; reductions in NO_x emissions in such locations bring NO_x and VOCs closer to similar proportions, increasing ozone concentrations. The largest 8-hour ozone disbenefit occurred in Richmond County, NY (0.62% decrease from 96.5 to 95.9 ppb)

For this paper, ambient concentrations of total PM were apportioned into nonvolatile and organic carbon-related PM as well as ammonium nitrate and ammonium sulfate based on the SANDWICH method described in (Frank 2006). All nitrates were assumed to exist as ammonium nitrate, and 12% of the water was assigned to ammonium nitrate. In most counties, the largest aircraft-related contributor to PM concentrations was ammonium sulfate, as shown in Figure 1.

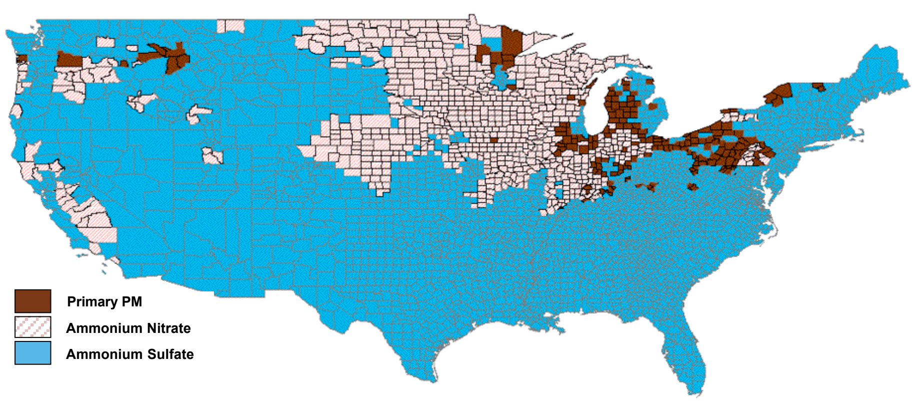

Figure 1: Largest aircraft-related contributor to ambient PM concentrations

2.3. Health impact assessment

The health impact assessment utilized the Environmental Benefits Mapping and Analysis Program (BenMAP) from Abt Associates, Inc. (Abt Associates Inc. 2005). The CMAQ results were input to BenMAP along with the year 2001 continental United States population and year 2000 baseline incidence and prevalence rates of a variety of illnesses. Monetary valuation was not done in the Energy Policy Act study, but valuations were computed for this paper in year 2001 dollars.

2.4. Health effects of aircraft emissions in the continental U.S.

The total health costs as well as costs and incidences for three most expensive health endpoints (by point incidence) are shown for $PM_{2.5}$ concentrations in Table 2 and ozone in Table 3. Premature mortality of adults age 30 and over from $PM_{2.5}$ exposure was 93% of all health costs.

Table 2: Three most expensive health effects of $PM_{2.5}$ exposure due to aircraft

Total cost of all endpoints for $PM_{2.5}$ exposure ($ millions)[1]: $955

	Incidences (90% C.I.)[2]	Cost (91% C.I.)[3]
Premature mortality (3% discount)[4]	160 (64 – 270)	$882 ($196 - $1830)
Chronic bronchitis (adults age 27 - 99)	110 (20 – 200)	$40 ($3 - $139)
Non-fatal myocardial infarction (3% discount, adults age 18 - 99)[5]	290 (160 – 430)	$26 ($7 - $57)

Table 3: Three most expensive health effects of ozone exposure due to aircraft

Total cost of all endpoints for ozone exposure ($ millions)[6]: -$2

	Incidences (90% C.I.)	Cost (91% C.I.)

[1] Valuation not available for all endpoints related to PM exposure in EPAct study; likely that costs represented by missing endpoints are less than $10 million based on other EPA analyses (U.S. Environmental Protection Agency 2007b).
[2] Rounded to the nearest whole number and to two significant figures where applicable.
[3] 2001 U.S. dollars. Rounded to the nearest whole number and to three significant figures where applicable. 4.5th and 95.5th percentiles presented as given by BenMAP.
[4] Due to chronic exposure to PM.
[5] Discounting applied as done for EPA's 2005 Clean Air Interstate Rule regulatory impact analysis (U.S. Environmental Protection Agency 2005b).
[6] Valuation not available for all endpoints related to ozone exposure in EPAct study; likely that costs represented by missing endpoints are less than $1 million based on other EPA analyses (U.S. Environmental Protection Agency 2007a).

Total cost of all endpoints for ozone exposure ($ millions)[6]: -$2

	Incidences (90% C.I.)	**Cost (91% C.I.)**
Emergency room visits for asthma (age 0 – 99)	-4 (-12 – 0)	$0 (-$0 – $0)
Hospital admissions–acute respiratory causes (children, age 0 – 1 for incidences, age 0 – 2 for valuation)	-6 (-3 – -10)	$0 (-$0 – -$0)
Premature mortality (all ages)[7]	0 (0 – -1)	-$2 (-$5 – -$1)

A further exploration of premature mortality due to $PM_{2.5}$ exposure was done using the EPAct and FOA3 inventories. CMAQ was not executed for the FOA3 inventory; instead, health incidences from the EPAct study were scaled based on differences between the two inventories. It was determined that incidences of premature mortality were primarily located in California for both inventories, as shown in Table 4.

Table 4: Five counties with highest PM mortality incidences (costs in $ millions)

	Energy Policy Act				FOA3			
Rank	**County**	**State**	**Incidences (Percent of Total**	**Cost (Percent of Total)**	**County**	**State**	**Incidences (Percent of Total)**	**Cost (Percent of Total)**
1	Los Angeles	CA	29 (18%)	$155 (18%)	Los Angeles	CA	30 (18%)	$160 (18%)
2	Orange	CA	8 (5%)	$43 (5%)	Orange	CA	9 (5%)	$47 (5%)
3	San Diego	CA	6 (3%)	$29 (3%)	San Diego	CA	6 (4%)	$34 (4%)
4	San Bernardino	CA	5 (3%)	$29 (3%)	San Bernardino	CA	6 (4%)	$32 (4%)
5	Cook	IL	5 (3%)	$27 (3%)	Riverside	CA	5 (3%)	$27 (3%)
All other counties			*110 (68%)*	*$598 (68%)*	*All other counties*		*87 (60%)*	*$467 (60%)*

To explore the impact of various PM species concentrations on premature mortality, health incidences and costs were apportioned by assuming that each species of PM has the same health impact per unit mass. Confidence intervals were not computed. The continental U.S.-wide results are shown in Table 5 for the EPAct and the FOA3 inventory.

[7] Due to acute exposure to ozone; based on Bell et al. 2004 study as used in (U.S. Environmental Protection Agency 2007a).

Table 5: Apportionment of health impacts to $PM_{2.5}$ species concentrations

Inventory		Nonvolatile Primary	Organics Primary	Ammonium Nitrate	Ammonium Sulfate from SO_x	Ammonium Sulfate from Primary PM	Total
EPAct	Incidences	23	30	30	75	6	160
	Costs ($ mil)	$122	$162	$163	$401	$34	$882
	Percent total	14%	18%	18%	45%	4%	
FOA3	Incidences	8	9	29	97	1	140
	Costs ($ mil)	$42	$47	$156	$518	$3	$767
	Percent total	5%	6%	20%	68%	0%	
EPAct/FOA3 factor difference		*2.9*	*3.4*	*1.0*	*0.8*	*10.3*	*1.2*

Concentrations of ammonium sulfate from SO_x emissions dominated the impacts for both inventories continental U.S.-wide and also for Los Angeles County (46% of total PM-related premature mortality costs in the EPAct inventory and 66% in the FOA3 inventory). PM-related premature mortality incidences were also apportioned to emissions of primary PM and secondary PM precursors, and the results are shown in Table 6.

Table 6: Apportionment of emissions to health costs

Inventory		Nonvolatile PM	Organics PM	NO_x	SO_x	Sulfates PM
EPAct	Marginal damage ($/kg)	$132	$340	$2	$43	$47
	Total cost ($ millions)	$122	$162	$173	$379	$34
	Percent grand total	14%	18%	20%	43%	4%
FOA3	Marginal damage ($/kg)	$152	$346	$2	$46	$47
	Total cost ($ millions)	$42	$47	$168	$477	$3
	Percent grand total	5%	6%	22%	62%	0%
EPAct/FOA3 factor difference		*2.9*	*3.4*	*1.0*	*0.8*	*10.2*

Marginal damages and total emitted mass must be considered together to understand the total health cost. For instance, organics-related primary PM has the greatest marginal damage, but is emitted in relatively small amounts (compared to NO_x and SO_x) and thus does not dominate the total health costs.

3. Areas of policy focus

An understanding of health costs due to aircraft emissions can illuminate areas of policy focus for changing aircraft emissions-related standards. Aircraft regulations and emissions are related to influences on air quality and human health in the impact pathway in Figure 2.

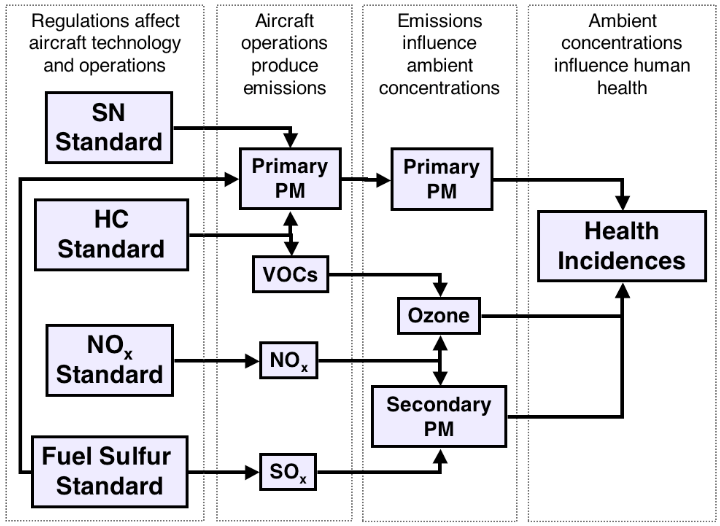

Figure 2: Pathway of influences from aviation regulations to human health effects. Arrows represent influences.

3.1. Emissions standards

The SN standard was designed to address visibility concerns, but SN has been correlated with nonvolatile PM emissions in FOA3 and FOA3a (Ratliff, Sequeira, Waitz, et al. 2008). ICAO and EPA SN standards generally allow smoke to increase with decreases in rated thrust. Nonvolatile primary PM was the second most damaging emission per unit mass but was responsible for the least total health costs because it accounted for 1% or less of the total emitted mass.

Nonvolatile primary PM emissions could be addressed through changes in engine technology, as combustor technology strongly influences nonvolatile primary PM formation. This strategy will require time and money to develop and distribute the new technology. Policymakers may be able to address nonvolatile primary PM relatively quickly by reducing the aromatics content in fuel, since fuels with high aromatics content produce more nonvolatile PM when combusted (Chevron Corporation 2006).

Volatile primary PM from hydrocarbons had the highest marginal damage of all aircraft emissions but only the third highest total health cost. The hydrocarbon standard has not been changed in the United States or at the international level since its creation (Code of Federal

Regulations 2005, International Civil Aviation Organization 2005). Unburned hydrocarbons form a portion of the volatile primary PM mass and also affect health impacts due to ozone exposure because of their relationship to ambient VOCs (U.S. Environmental Protection Agency 2006b, Wey, Anderson, Wey, Miake-Lye, Whitefield and Howard 2007). CO can also affect ozone concentrations, but the relationship of VOCs to ozone is much more important (U.S. Environmental Protection Agency 2006b). FOA3 and FOA3a assume that the mass of volatile primary PM from hydrocarbons scales directly with the hydrocarbon emissions of aircraft engines.

The NO_x standard has changed several times at the international and U.S. levels since its creation, and the current ICAO and EPA standards allow engines with larger pressure ratios to produce more NO_x. NO_x emissions had the lowest marginal damage per unit mass but the second highest total health cost because NO_x was a majority of the emitted mass. Increasing NO_x stringency will require changes in engine technology, potentially costing manufacturers and airlines substantial resources. Because engine fuel efficiency increases with increasing pressure ratio, reductions of pressure ratio to control NO_x formation can cause increases in CO_2 production, leading to a tradeoff between NO_x and CO_2 emissions.

3.2. Fuel standard

The fuel sulfur standard is important because it influences the formation of volatile primary PM and ammonium sulfate particles. Sulfates-related volatile primary PM had a marginal damage of approximately $47 per kilogram, while SO_x emissions caused damages of approximately $43 to $46 per kg. The amount of SO_x mass produced caused SO_x emissions to dominate the total health costs in the continental U.S. as well as in Los Angeles County. It is possible to remove sulfur from petroleum-based jet fuel using the process of hydrodesulfurization (HDS); this process, however, also changes other fuel properties (Chevron Corporation 2006, Massachusetts Institute of Technology and RAND Corporation 2007).

A switch to a lower-sulfur fuel may not require substantial changes in aircraft or engine technology. Production of such a fuel would require changes in refineries, but the EPA has already mandated a reduction of sulfur in diesel fuel to 15 ppm (U.S. Environmental Protection

Agency 2004c). Addressing aviation fuel sulfur content could be an effective way to address aircraft-related health impacts due to air quality changes. Note that reductions in SO_x emissions may allow more ammonium nitrate particles to form.

3.3. Assessment of fuel sulfur stringency

An inventory generated with assumption of ultra low sulfur (ULS, or 15 ppm fuel sulfur content) fuel was assessed to explore a sulfur stringency strategy. The inventory was assembled by James Hileman at the Massachusetts Institute of Technology using FAA's AEDT/SAGE inventory (Federal Aviation Administration 2006) for the year 2005 and FOA3; it was compared to an AEDT/SAGE inventory of the same year assembled assuming a fuel sulfur content of 600 ppm. Both inventories contained 515 airports representing 243 of the 273 counties with airports in the Energy Policy Act study.

The results of the comparison are shown in Table 7; emissions related to fuel sulfates were reduced by a factor of 40. The fuel switch reduced aviation-related mortality incidences in Los Angeles County by a factor of 2 (20 incidences to 10 incidences).

Table 7: Health incidences due to emissions from AEDT 600 ppm and ULS inventories

Inventory		Nonvolatile Primary	Organics Primary	Ammonium Nitrate	Ammonium Sulfate from SO_x	Ammonium Sulfate from Primary PM	Total
600 ppm	Incidences	5	6	30	65	0	**110**
	Costs	$28	$31	$161	$345	$3	**$567**
	Percent total	5%	5%	28%	61%	0%	
ULS	Incidences	5	6	53	2	0	**65**
	Costs	$28	$31	$281	$9	$0	**$349**
	Percent total	8%	9%	81%	2%	0%	
600 ppm/ULS factor difference		*1.0*	*1.0*	*0.6*	*40.1*	*40.1*	***1.6***

Other factors must be considered when analyzing the effects of ULS fuel. First, the EPA determined that ULS diesel fuel would have a 1.5% lower volumetric energy content (U.S. Environmental Protection Agency 2000b), and a similar loss may occur for ULS aviation fuel (Massachusetts Institute of Technology and RAND Corporation 2007), meaning that aircraft will need more fuel to fly a given distance. Next, the EPA has estimated that a switch to ULS diesel fuel will cost refineries an additional 4 cents to 12 cents per gallon in various portions of the U.S (U.S. Environmental Protection Agency 2000a). The AEDT ULS inventory represented flights that burned approximately 2 billion gallons (6.7 megatonnes) of fuel in the U.S. in the year 2005, which represents an increase in fuel production costs of approximately $132 million, assuming a 6-cent increase in costs per gallon burned. This is $17 for every kilogram of fuel sulfur-related emissions (SO_x and sulfate-related primary PM) eliminated.

The total health costs avoided by an immediate switch to a ULS fuel (vs. using fuel with a sulfur content of 600 ppm) was $218 million, suggesting that the health benefits of a switch to ULS fuel may be comparable to the economic costs. SO_x and sulfate-related primary PM each cost approximately $40 per kilogram emitted. Note that this cost-benefit analysis only takes into consideration refinery production costs and air quality-related health benefits due to reductions in ambient $PM_{2.5}$ exposure. However, a switch to ULS fuels also has implications for the global climate. Decreases in sulfate particles could cause a net warming of the earth's climate, as sulfate has a cooling effect. The cost-benefit analysis in (Hileman 2007) using the Aviation Environmental Portfolio Management Tool (APMT) (Partnership for AiR Transportation Noise and Emissions Reduction 2007) indicated that the costs due to climate warming may outweigh the benefits due to improved air quality. Ultimately, policymakers must weigh these tradeoffs when considering a fuel switch.

3.4. Assessment of NO_x stringency

Addressing NO_x may also be important to mitigate the air quality-related health effects of aircraft. In 2004, CAEP's Forecasting and Economic Analysis Support Group (FESG) analyzed the economic effects of increasing CAEP/4 NO_x standards (International Civil Aviation Organization 2004). The group estimated recurring and non-recurring costs to engine manufacturers as well as the costs of additional fuel, weight, landing fees, and maintenance for airlines. Health effects were not explored.

FESG determined that the most cost-effective option was a 10% increase in NO_x stringency over CAEP/4 with implementation in the year 2008, which would lead to a cumulative NO_x reduction of 146,000 tonnes across the global aviation fleet in a 2002 – 2020 window with no increase in CO_2. The investment cost necessary to eliminate a tonne of NO_x was determined to be approximately $20 to $30 per kilogram in 2002 dollars (3% discount rate). While a direct comparison with the health impact assessment is difficult, note that NO_x health costs were determined to be just $2 per kilogram. This may suggest that addressing NO_x to mitigate air quality-related health effects is not cost-beneficial.

Conclusion

This paper assessed the results of a study of how aircraft affect United States air quality, mandated by the Energy Policy Act of 2005. The study estimated that aircraft are responsible for 160 yearly incidences (90% C.I. of 64 to 270 incidences) of premature mortality of adults age 30 and over ($882 million in year 2001 dollars, with a 91% CI of $196 to $1830 million) due to influences on ambient $PM_{2.5}$ concentrations in the continental U.S. This represents 93% of all health costs due to exposure to aircraft-related $PM_{2.5}$ and ozone concentrations, and 18% of the total premature mortality costs from $PM_{2.5}$ occurred in Los Angeles County.

The EPAct study utilized aircraft emissions inventory generated using FOA3a, a conservative modification of ICAO FOA3, to predict aircraft PM emissions. SO_x emissions were underestimated by approximately 20% in EPAct inventory due to a misapplication of the fuel sulfur assumption for 78 airports. This paper also utilized an inventory generated using FOA3 and a consistent fuel sulfur assumption of 680 ppm. Based on an assessment of both inventories, it was estimated that aircraft were responsible for 140 to 160 yearly incidences of premature mortality from exposure to ambient $PM_{2.5}$. Ammonium sulfate concentrations caused 46% to 69% of the incidences, while ammonium nitrate caused 18% to 20%. Organics related volatile primary PM caused 6% - 18%, nonvolatile primary PM caused 5% - 14%, and sulfates-related volatile primary PM caused 0% to 4% of the incidences.

Based on the results, it was determined that changing regulations governing NO_x emissions and fuel sulfur content may be effective strategies to mitigate incidences of premature mortality due to aircraft. Changing to ultra-low sulfur fuel across the continental U.S. would reduce incidences of premature mortality continental U.S.-wide by approximately 40% ($218 million) and cause a factor of 2 reduction of incidences in Los Angeles County. The cumulative additional costs to refineries to produce 15-ppm fuel could be approximately $132 million (6 cents per gallon, or $17 for every kilogram of fuel sulfur-related emissions eliminated), suggesting that the benefits may be comparable to the costs. However, the costs of climate warming due to sulfate removal may outweigh the air quality-related health benefits.

Finally, a brief exploration was done of ICAO CAEP FESG's NO_x stringency assessment. FESG predicted that an industry-wide investment of $30 - $40 would be required for every kg of NO_x eliminated if the ICAO NO_x standard were to be increased by 10% in the year 2008. However, this paper determined that NO_x has air quality-related health costs of only $2 per kg.

Further research

There are many avenues for further research. First, the policy-making community needs improvements in the knowledge and modeling of particulate matter chemistry. There are large differences between the FOA3 and FOA3a models, and an understanding of how the health effects of specific PM species may differ is also needed. Researchers must also continue to quantify the uncertainty in PM monitoring and species apportionment methods and technologies. Some PM species (particularly nitrates) evaporate from EPA monitors, and this lost mass is currently inferred. The mass of particle-bound water changes based on ambient conditions and thus is also inferred. The SANDWICH method assigns 12% of the inferred particle-bound water mass to nitrates (Frank 2006). Ammonium sulfate still dominated nationwide using an upper bound assignment of 50%, but the quality of the apportionment assumption will become more important as policymakers and researchers desire finer resolution.

Finally, researchers must compare aircraft emissions with other aviation-related emissions such as from ground support equipment. Other airport-related sources such as power plants and vehicles traveling to and from airports also affect emissions inventories. Generally, emissions inventories that include aircraft and non-aircraft sources have not been created.

Aviation growth over the next several decades will increase the importance of understanding aviation's health effects. As aviation plays an important role in the global economy, a continual assessment of aviation's environmental effects is critical. A better understanding of aviation-related PM and the pathway from standards to health effects can lead to better regulatory strategies.

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