# QUANTIFYING THE RELATIONSHIP BETWEEN AIR TRAFFIC MANAGEMENT INEFFICIENCY, FUEL BURN AND AIR POLLUTANT EMISSIONS

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## Abstract

Worldwide air travel demand has increased significantly over the past 30 years, leading to an increased number of flights, associated delays, fuel consumption, and aircraft air pollutant emissions. Demand for aviation is expected to grow three-fold over the next two decades and could potentially lead to an increase in aviation related emissions of air pollutants. This study quantifies the contribution of aircraft emissions at 148 airports that lie within the air quality non-attainment or maintenance areas to the county-level emissions inventories. We also quantify how inefficiency in air traffic management contributes to increased aircraft-related fuel burn and emissions. A baseline fuel burn and emission inventory is presented, consisting of realistic aircraft operations and including delays due to air traffic management inefficiencies. At most of the evaluated airports (~52%), aircraft emissions are a relatively small contributor (<1%) to county level emissions of the criteria pollutants considered in this analysis. Reducing ground delays can significantly impact those airports with high taxi times, leading to potential airport reductions of between 10% and 25% in fuel burn and emissions. A sample efficiency initiative is used to demonstrate the potential reduction in delays, and hence, in fuel burn and emissions.

## Introduction

The demand for air travel has increased significantly worldwide over the past 30 years and this has led to an increased number of flights, delays, fuel consumption, and emissions of air pollutants from aircraft. Over the next two decades, the demand for aviation is expected to grow three-fold. The FAA and other members of the Joint Planning and Development Office (JPDO) have identified delay reduction as an enabler for continued aviation growth. Recent aviation fuel prices along with changes in public awareness of oil dependence and the need for fuel conservation demonstrate the timeliness of an analysis that quantifies the potential benefits of delay reduction on fuel burn. More efficient operations will reduce not only the total fuel burn but also the associated emissions.

This study is designed to investigate how inefficiency in air traffic management contributes to increased aircraft-related fuel burn, and hence, emissions of carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NOx), fine particulate matter (PM2.5) and oxides of sulfur (SOx) at airports within non-attainment and maintenance areas. There are four objectives of the study: (1) create a baseline aircraft fuel burn inventory for commercial service airports in non-attainment areas focusing on air pollutant emissions below the atmospheric mixing height (assumed to be 3000 above ground level); (2) evaluate the effect of auxiliary power unit (APU) usage on emissions; (3) quantify the maximum potential benefits of delay reduction; and (4) demonstrate the relationships among specific initiatives, delay reduction, fuel consumption and emissions.

A baseline fuel burn and emissions inventory consists of realistic aircraft operations that include delays due to air traffic management inefficiencies. The incremental contribution to the baseline inventory due to specific inefficiencies was identified to examine the potential benefits of improvements. The benefits were related to minutes of delay quantified as metric tons of fuel burned and emissions of air pollutants. Ground level emissions are comprised of emissions from aircraft main engines and APUs. From the local air quality perspective, ground-based initiatives are more relevant than other Air Traffic Control (ATC) initiatives. Given the relatively fixed flight path below 3000 feet, there are very few initiatives that would improve emissions while the aircraft is airborne yet below the mixing height.

In this study, we focus only on those US commercial service airports that lie within air quality non-attainment and maintenance areas as defined by US National Ambient Air Quality Standards [1].

# Baseline Inventory

Here we discuss our methods for estimating aircraft emissions of CO, HC, NOx, PM2.5 and SOx. The list of commercial airports located in an EPA-designated non-attainment or maintenance area for one or more of the criteria pollutants was obtained from the FAA's Voluntary Airport Low Emissions (VALE) program [2].

## *National Emissions Inventory Baseline Comparison*

The US Environmental Protection Agency's (EPA's) National Emissions Inventory (NEI) provides estimates of emissions from point, non-point, mobile, and biogenic sources [3]. Several pollutants are included in this inventory, which is collected every three years. In this study, the 2002 NEI county data was used to generate a baseline of county level emissions for the counties where the airports identified in the VALE program as in non-attainment or maintenance areas are located. Each airport is mapped to its corresponding county using federal information processing standards (FIPS). Any airport which may straddle county boundaries was allocated according to the county listed in the FAA National Airspace System Resources (NASR) database [4]. For counties with multiple commercial service airports, the overall aircraft emissions were aggregated to compute total emissions within the county.

## *Airport Aircraft Emissions Inventory*

A baseline emissions inventory for all aircraft operations at the non-attainment and maintenance area airports was generated using the most current FAA Enhanced Traffic Management System (ETMS) data for the period June 2005 through May 2006, thereby providing one year of operations at each airport. The original list of VALE airports in non-attainment and maintenance areas numbered 150, however not enough operational data was available for Block Island (Rhode Island) and Lake Hood (Alaska). Consequently, these two airports were not included in this study.

Direct emissions from the aircraft main engines and APUs are modeled. The FAA Aviation Environmental Design Tool Emissions and Dispersion Modeling System (AEDT/EDMS) version 5.0 [5] calculates the emissions based on aircraft/engine/APU combination, aircraft weight, aircraft taxi and ground delay time, annual average meteorological conditions at the airport, and airport field elevation. The detailed operations data required for the analysis were obtained in two phases. First, the Instrument Flight Rules (IFR) traffic data were collected as shown in Figure 1. Then, the Visual Flight Rules (VFR) operations were determined as shown in Figure 2.

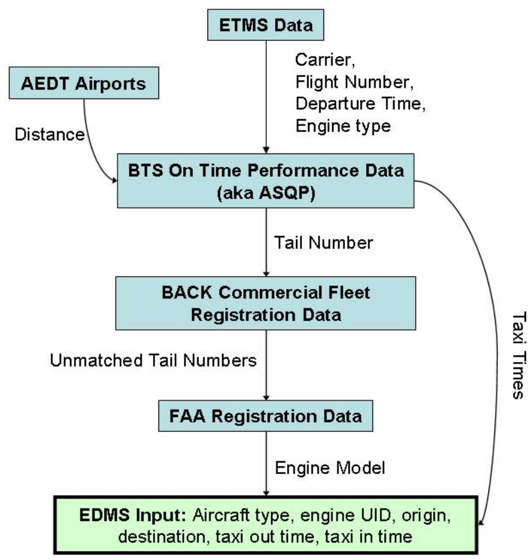


**Figure 1. IFR Traffic Data Collection Process**

All IFR traffic is derived from ETMS. ETMS provides the flight number, the origin and destination airport for the flight, and a generic aircraft type. However, the generic aircraft type is not suitable for modeling emissions, since the specific airframe and engine combination is required. The Bureau of Transportation Statistics (BTS) On-Time Performance database [6] was used to match flight numbers to the aircraft registration number (tail number) to relate each flight to a specific aircraft type. General Aviation flights operating under IFR procedures file their flight plans using their tail number.

The registration information for the aircraft was obtained from the commercially-available BACK fleet database [7] or the FAA's aircraft registration database [8]. These databases were used to determine the engine models installed on individual aircraft based on the tail numbers. The BTS data also provides aircraft pushback, wheels up, touchdown, and gate arrival times. This allowed the outbound and inbound taxi times to be calculated for input into EDMS. Since not all flights appear in the BTS data, flights not reported in BTS were assumed to have taxi times equal to the average of the reporting flights at the airport performing a similar operation during the same hour.

For VFR traffic that did not appear in the ETMS data, the operations were estimated by subtracting the IFR operations from the total operations for the airport as obtained from the Air Traffic Activity Data System (ATADS) [9]. The fleet mix of aircraft included in the VFR input to EDMS was estimated from the aircraft categories based at each airport. The method for generating the VFR operational data is shown in the first column of Figure 2. The operational data was combined with estimated aircraft weights and the APU survey results (described in the following section) to complete the EDMS tables needed for the calculation of emissions by airport.

The database of airport information developed for the FAA Aviation Environmental Design Tool (AEDT) [10] was then used to determine the trip length for the IFR flights. This trip length was used to estimate aircraft takeoff weight. VFR flights were assumed to operate at the maximum weights. These steps resulted in a table of aircraft/engine combinations and associated takeoff weights and taxi times for all IFR and VFR flights in a format suitable for use by EDMS. Using the IFR and VFR input data, EDMS was used to compute emissions for CO, HC, NOx, SOx, PM2.5, and the total fuel consumed for aircraft operations below 3000 ft as shown in Figure 2.

Aircraft operations were aggregated by airframe, engine and takeoff weight to ease the computational requirements of EDMS. The taxi in and out times were averaged across those operations. To be conservative, all operations were assumed to taxi in and out using all engines from pushback to wheels-off. Some carriers do use a single engine taxi, but the circumstances of single engine taxi use could not be adequately defined for consistent realistic modeling across the variety of carriers, airports and weather conditions. While some carriers switch to APU usage during periods of long delays (see APU survey results for more detail), less than 2% of the aggregated departures had an average taxi out time of greater than 30 minutes and the results of the APU survey did not reveal a consistent time when carriers switch between engines to APU.

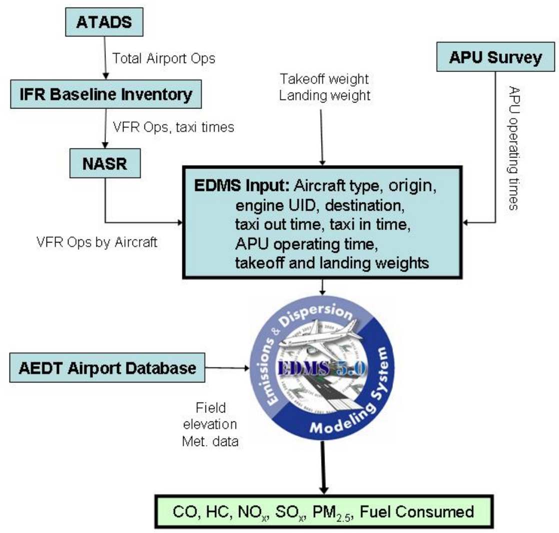


**Figure 2. VFR Traffic Data Collection and EDMS Emissions Inventory**

## APU Survey

Because airline APU-usage statistics are not part of the current DOT reporting systems, we performed a survey to determine typical usage. We found different levels of recording detail and time periods for data collected across the airlines. Although many carriers have standard operating procedures for when and how to use APUs, the ultimate decision rests with the pilot. There are at least four modes to consider when discussing APU usage:

- *Departure Preparations:* If ground-based support is available, APUs may be turned on just prior to pushing back from the gate, or, if no ground support is available, the APUs may be started to help prepare the cabin for passengers or cargo.
- *Departure Taxi:* Once the aircraft leaves the gate, the carrier may have a standard operating procedure or the pilot can use their discretion as to the use of the APU during taxi. If the engines are not producing the needed power to maintain the cabin environment or an excessive delay is expected, the APU may be used to supplement power for the aircraft.

- *Arrival Taxi:* When the aircraft lands and taxis to the gate, again the carrier's operating procedures and/or the pilots discretion are applied to determine the use of the APU.
- *Arrival to the Gate:* If power and conditioned air are available at the airport's gate, the APU might remain on until the aircraft is properly connected to the ground source. If no ground support is available, the APU may be shut off or remain operating, depending on when the aircraft will be used next or for maintenance purposes.

The data collected were proprietary and varied considerably among airlines. Because APU operations are specific to air carriers and the baseline analysis would be aggregated at an engine-airframe combination level ignoring the carrier, the APU times were assigned based on whether the aircraft was a single aisle, narrow body design or a multiple aisle, wide-body design. Table 1 shows the APU usage times in minutes per landing and take off cycle (LTO) for the study. Due to the nature of the data, the specific amount of time an APU was used during taxi was unable to be determined. Hence, it was assumed that APU time represents time the APU is used at the gate.

| Narrow Body | | | Wide Body | | |
|---|---|---|---|---|---|
| Lower | Medium | Upper | Lower | Medium | Upper |
| 31 | 48 | 65 | 96 | 130 | 163 |

**Table 1. APU Use in Minutes per LTO**

The range of values provided in Table 1 were used to evaluate the contribution of APUs to total aircraft emissions. The medium values were used in the baseline fuel burn and emissions inventory.

### *Maximum Potential Benefits*

To estimate the upper limit of emissions reductions that might be realized by reducing ground delay, the baseline emissions inventory for each airport was compared with an emissions inventory calculated assuming aircraft taxi and departures were unimpeded. The direct comparison of actual taxi times to unimpeded taxi times was chosen because of the focus on aviation emissions below 3000 feet (the mixing height).

## Identification of Fuel Conservation Measures

The US Joint Planning and Development Office has a long range plan for improving the service of the national airspace while maintaining safety and improving environmental quality based on a series of Next Generation (NextGen) technologies [9]. The JPDO's NextGen objectives are not achievable with the current state of the National Airspace System (NAS). The FAA is exploring several initiatives to bridge the gap between the current and future systems.

Since the scope of this study is limited to local air quality impacts, we have constrained the strategies to those that affect ground-based delays. Twenty-four initiatives were considered because they are anticipated to have either a direct or indirect effect on aircraft operations below 3000 feet. These initiatives belong to the following general categories:

- New and Extended Runways
- Schedule De-Peaking
- Integrated Weather Technology
- Improved Traffic Flow Collaboration
- Filling Gaps in Arrival and Departure Streams
- Efficient Arrival Flows
- New Arrival and Departure Routes
- New Approach Procedures
- Reduced Separation Standards
- Improved Surface Efficiency

## Opportunities to Reduce Inefficiencies

Radar data from April 2005 was available and was used to identify time periods where airports that reside in non-attainment or maintenance areas experience congestion. Using ASPM data for the same time period, taxi-out times for each airport were chosen as the primary indicator of congestion. We identified airports where an operational initiative may improve fuel consumption by reviewing programs in the FAA Operational Evolution Plan (OEP) [11], National Climatic Data Center (NCDC) information, and the airport taxi-out times.

Implementation of Airspace Flow Programs (AFPs) instead of Ground Delay Programs (GDPs) in support of a Severe Weather Avoidance Plan (SWAP) was used to estimate a range of potential benefits of delay reduction and fuel conservation measures.

Before the inception of AFPs, GDPs were used to alleviate airspace congestion when convective weather occurred. The FAA would then define a Flow Constrained Area (FCA) and would reroute aircraft using SWAP routes. In addition, GDPs were implemented to help reduce the flow through the FCA. However, GDPs were targeted at specific airports and some airports received a larger amount of delay when compared to other airports in the region. In addition, it was difficult to control en route congestion by controlling flights on the ground. With the introduction of AFPs, the FAA can now constrain a region of airspace during convective weather events. The AFP combines the power of GDPs and FCAs to allow more efficient, effective, equitable, and predictable management of airborne traffic in congested airspace.

The use of AFPs instead of GDPs in support of a SWAP leads to reduced taxi-out times from airports that are affected by severe weather. By metering the flights through a region of congested airspace, arrivals to airports are also metered. This allows departures to occur through the natural spacing of the arrivals.

A previous analysis had been performed to determine if increases in taxi-out times would be less when AFPs were used instead of GDPs was used to support the modeling of this initiative [12]. ASPM and weather data from April 20, 2005 at Boston's Logan Airport (BOS) was selected for this analysis. Although a GDP in support of a SWAP at BOS was not used on this day, convective weather did occur and SWAP routes were in place. The analysis referenced above found that when GDPs were used in support of a SWAP, taxi-out time increased 30% over taxi-out times when SWAP reroutes were not in use. When AFPs were used in support of SWAP reroutes, the increase of taxi-out time was only 20% higher than when SWAP reroutes were not in use. This decrease was applied to the taxi-out times for the April 20, 2005 time period to account for the taxi-out savings of using AFPs instead of GDPs in support of SWAP reroutes.

# Baseline Emissions

The results in this paper are presented in order of narrowing focus. The beginning is a comparison of the relative contributions of aviation emissions on county-level air quality emissions inventories. The emissions at 148 airports and the percentage of maximum benefit from reducing delay are reported. Finally, analyses of the potential fuel and emissions benefits of the Airspace Flow Program relative to Ground Delay Programs at Boston are presented to demonstrate the impact of a specific technology.

## *NEI Comparison Analysis*

Using the processes outlined above, EDMS was used to calculate the aircraft emissions below 3000 ft at 148 airports (ground support equipment was not included). These 148 airports account for approximately 59% of domestic IFR departures and represent about 80% of US fuel burn and emissions from aircraft with engines greater than 26.7 kN output. [13]

These 148 are in 134 counties; however, NEI data was not available for the two of Alaskan counties, so a total of 145 airports were considered for comparative analysis against NEI emission inventory. Figure 3 is the histogram of the number of counties with the associated percentage of the aircraft related county level emissions. The EDMS results were based on the actual operations and the medium level of APU usage. Particulate Matter emissions are only based on aircraft engines with smoke numbers in ICAO emissions database. Particulate Matter is reported in the NEI at two levels, matter less than 10 $\mu m$ in diameter (PM10) and matter less than 2.5 $\mu m$ in diameter (PM2.5). While aircraft only emit PM2.5, the NEI reports county emissions for both. Aircraft operations in 75 of the 132 counties included in the analysis contribute less than 1% of the county emissions for all six pollutants.

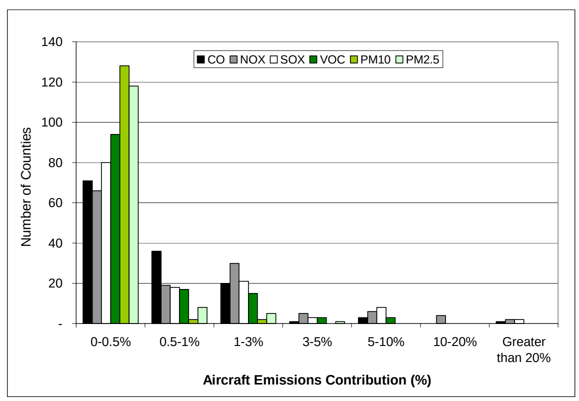


**Figure 3. Aircraft Emissions Contribution to 132 Counties Based on 145 Airports**

Twelve counties have more than 5% of their county-level NOx emissions from aircraft. Only one of these counties has more than one airport. Eleven of these counties have over 100,000 annual LTOs. Three out of the six counties with aircraft emissions contributing more than 10% to county-level emissions have over 200,000 annual LTOs.

Ten counties have more than 5% of their county-level SOx emissions from aircraft. Only one has fewer than 100,000 annual LTOs. One of the two counties with aircraft emissions contributing more than 20% to county-level emissions has more than 400,000 LTOs.

## APU Contribution to Aircraft Emissions

This analysis measured the emissions of aircraft at all 148 airports throughout the operational cycle below 3000 feet. Without sufficient information on how APUs were used, a survey was undertaken so that the APU's effect on emissions could be modeled as correctly as possible. The APU contributions shown below are based on the three levels of APU usage for narrow and wide body aircraft as described in Table 1. In Figure 4, the amount of criteria pollutants according to the estimated APU usage ranged from almost 0% to about 30% of total aircraft emissions. The average of the percentage remains under 10% for all pollutants with lower and medium levels of APU usage. In fact, it is below 5% for CO, NMHC and VOC. For the medium levels of APU usage, only four counties have more than 1% of their NEI county NOx emissions attributed to APUs. These counties each have an airport with over 100,000 annual LTOs. Three counties (each with over 100,000 annual LTOs) have more than 1% of the county SOx emissions attributed to APUs. Two counties have more than 1% of their county-level emissions for both NOx and SOx. For VOC and CO, all counties had less than 1% of the county emissions contributed by the medium level APU usage.

It should be noted that these results reflect a uniform application of the values presented in Table 1. For certain small business jets, an hour of APU time (the upper value) can produce enough SOx emissions that they will represent more than 30% of the emissions from the LTO cycle below 3000 ft when the taxi times are small.

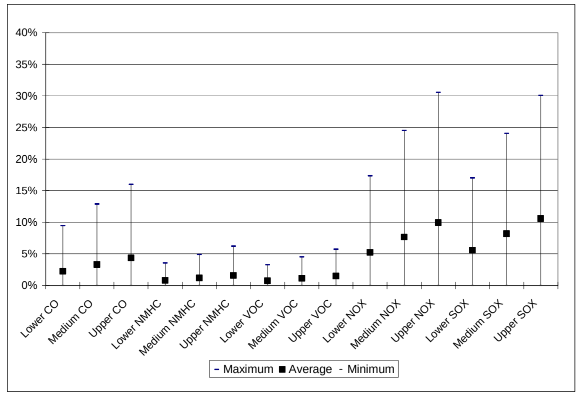


**Figure 4. Range of Total Estimated Actual Flight Operations' Emissions Attributed to APU Using Three APU Usage Levels**

The total aircraft emissions used to generate Figure 4 included ground delay. In order to determine the effect of the APU on general aircraft emissions, APU emissions were compared to the rest of the aircraft emissions under a no delay scenario. For this analysis, the unimpeded taxi times used to assess the potential benefits of reducing delay were used. Figure 5 shows how removing delay increases the importance of APU usage in determining the overall emissions for aircraft. The means of CO, NOx and SOx increase under all three usage levels, while NMHC and VOC remain about the same.

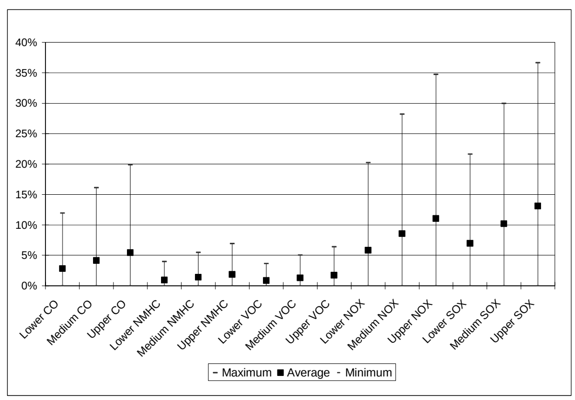


**Figure 5. Range of Total Estimated Unimpeded Operations' Emissions Attributed to APU Using Three APU Usage levels**

Both IFR and VFR operations were used in determining the percentage effect of APUs for Figures 4 and 5 in order to reflect the full spectrum of aircraft at each airport, not just the aircraft with APUs. While the upper range of some of these values may seem quite high (greater than 20%), it is important to note that these maximum values are rare and tend to be smaller airports with business jet operations. The combination of low taxi times and a uniform application of the APU survey estimates to small business jets lead to APUs contributing a high percentage of the aircraft emissions. However, the APUs at some larger airports (four in this analysis) contribute more than 1% to the county level emissions.

## Potential Benefits from Reduced Ground Delay

Originally, all 148 airports were included in the analysis of potential benefits due to reduced ground delay. However, several airports (35) lacked appropriate BTS information about taxi times. According to previous standard emissions modeling practices, these aircraft should be assigned the standard taxi times of 19 minutes on departure and 7 minutes on arrival. Reducing these flights to unimpeded taxi times may artificially raise the potential benefits of reducing ground delay since these default times are higher than those typically measured at airports. Therefore, airports with only the default taxi-in and taxi-out times were removed from this analysis. This left 113 airports. The emissions of the actual and unimpeded operations were estimated using the normal APU times.

In Figure 7, the number of airports with each level of fuel savings is reported. The smallest amount was about 23 metric tons over a year while the largest savings was over 86,000 metric tons. The total across the 113 airports was over 985 million kg (985,000 metric tons) of fuel.

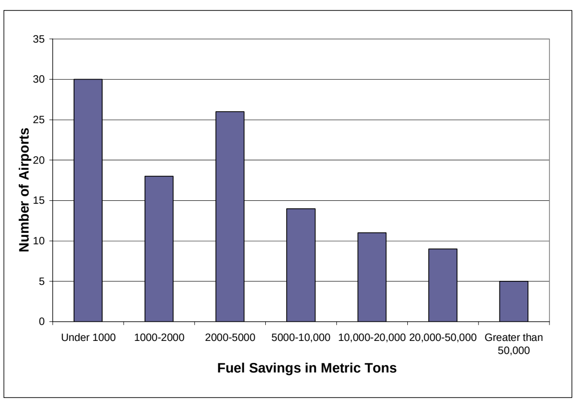


**Figure 7. Potential Fuel Savings in Metric Tons Due to Reduced Ground Delay**

The total metric tons of fuel saved translate into an average saving of 21% across the included airports. Figure 8 shows the number of airports with various levels of percentage improvements. Airports with fewer operations may experience a higher percentage gain as the smaller fuel changes are a larger portion of the total fuel burn.

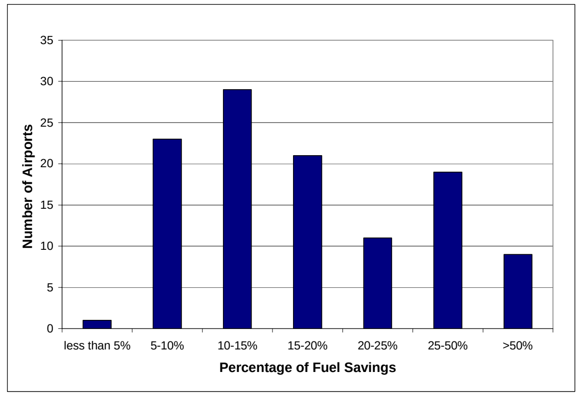


**Figure 8. Potential Fuel Savings as a Percentage of Total Fuel Burn Due to Reduced Ground Delay**

Aggregated across the 113 airports, Table 2 shows the potential annual change in pollutants that result from the reduction in ground delay.

| Pollutant | Mass (metric tons) | Percentage |
|---|---|---|
| Carbon Dioxide | 26702 | 21% |
| Non-Methane Hydrocarbons | 3809 | 15% |
| Volatile Organic Compounds | 4088 | 15% |
| Nitrogen Oxides | 4007 | 6% |
| Sulfur Oxides | 1341 | 16% |
| Particulate Matter < 2.5 µm | 113 | 13% |

**Table 2. Potential Pollutant Reduction Due to Reduced Ground Delay**

## Airspace Flow Program

The Airspace Flow Program was evaluated in a five hour time frame at BOS. Even in this short time period, improvements in fuel burn and emissions were apparent. Compared to the GDP, the AFP would have reduced CO by almost 14% and fuel could have been saved by up to 10%. Table 3 contains the mass and percentage change for select pollutants and fuel.

| | Mass (Kg) | Percentage |
|---|---|---|
| Carbon Monoxide | 204 | 14% |
| Non-Methane Hydrocarbons | 34 | 8% |
| Volatile Organic Compounds | 36 | 8% |
| Nitrogen Oxides | 35 | 4% |
| Sulfur Oxides | 11 | 10% |
| Particulate Matter < 2.5 *µm* | 1 | 8% |
| Fuel | 8021 | 10% |

**Table 3. Modeled Pollutant and Fuel Reduction Based on AFP Compared to GDP at BOS for a Five Hour Period**

The Airspace Flow Program is one example of how current programs being pursued by the FAA can incrementally change operations to reduce delay. By reducing delay, fuel burn and emissions are reduced.

## Summary

For most of the airports considered in this study, aircraft emissions for NOx, CO, VOC, PM2.5 and SOx account for less than 1% of county level emissions. For 12 counties, aircraft NOx emissions are greater than 5% of the county emissions that include some of the busiest airports in the NAS. Reducing ground delays can significantly impact those airports with high taxi times, leading to potential airport reductions of between 10% and 25% in fuel burn and emissions. While most airports with the percentage changes greater than 25% are smaller airports, airports with over 150,000 operations have an average fuel savings of 18% due to reduced taxi times. An analysis of one sample initiative was used to demonstrate the potential to reduce ground delays, thereby reducing fuel burn and emissions.

## Acknowledgements

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## *Keywords:*

Energy Policy Act of 2005, aircraft PM, emissions, local air quality.

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## Biographies

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