Alternative fuels as a means to reduce PM$_{2.5}$ at airports

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ABSTRACT

The Alternative Fuels as a Means to Reduce PM$_{2.5}$ at Airports project (ACRP 02-23) was undertaken to investigate the impact that alternative fuel use could have on emissions and ambient air pollution concentrations of fine particulate matter (PM$_{2.5}$) at airports. This paper presents an overview of the ACRP02-23 project and results. The results are based on modeling of emissions and ambient air pollution concentrations at five case study airports for those sources that contribute most to PM$_{2.5}$ emissions. Alternative fuels were selected for analysis primarily based on their potential to reduce PM$_{2.5}$, and were limited to those with short-term (i.e., fewer than 10 years) commercial availability and available emissions data. The largest emission reductions occurred when alternative jet fuel was used in aircraft and auxiliary power units (APUs). This was followed by: replacing diesel-fueled ground support equipment (GSE) with GSE powered by electricity, fueled by liquefied petroleum gas (LPG), or fueled by compressed natural gas (CNG); gate electrifications; and replacing GSE diesel with biodiesel. In terms of air quality impact, the highest air pollution impact reductions generally occurred when diesel-fueled GSE were replaced with electric, LPG or CNG equivalents, followed by alternative jet fuel use in aircraft and APUs, replacing GSE diesel with biodiesel, and gate electrification.

BACKGROUND

Airport managers, environmental agencies and others in the aviation industry are becoming increasingly aware of the contribution of airport-related activities to local and global air quality. Local air quality, in the context of an airport, is typically defined as the emissions directly associated with sources at an individual airport. Air quality concerns include actual local emissions, and perceived emissions and their impact. These concerns can slow and inhibit the review and approval process of airport development projects. For local air quality, the National Ambient Air Quality Standards (NAAQS) (1) criteria pollutants include ozone (with the associated precursors volatile organic compound (VOC) and oxides of nitrogen (NO$_x$) emissions), sulfur dioxide (SO$_2$), nitrogen dioxide (NO$_2$), course particulate matter (PM$_{10}$), fine particulate matter (PM$_{2.5}$), and lead (Pb).

A geographic area possessing ambient concentrations in excess of the NAAQS is considered “non-attainment” of that NAAQS, and an area possessing ambient concentrations below the applicable NAAQS is considered “attainment”. More than 50 commercial service airports in the U.S. are located in PM$_{2.5}$ non-attainment areas (2). Over time, additional locations may be subject to PM$_{2.5}$ non-attainment designations because the standards are often tightened following the NAAQS review every five years. Many airports around the country are developing emission reduction plans identifying actions that can be undertaken to reduce airport-related PM$_{2.5}$ emissions, especially in areas of non-attainment. One particular way in which PM$_{2.5}$ emission can be reduced is via the use of alternative fuels, due to their lower sulfur and aromatic content which reduces the formation of particulate matter. Other strategies to address local air quality concerns close to airports include reducing delay and improving operational efficiency of mobile sources (3, 4).

Various opportunities exist for alternative fuels to be used at airports (e.g., buildings, aircraft, and ground vehicles in airport controlled areas). However, many of the main sources of airport-related PM$_{2.5}$ emissions (and the primary potential users of alternative fuels) are not under the direct control of airport operators in terms of the emission sources. These include airport-related access roadways and their associated road vehicles, ground support equipment (GSE) and aircraft. Airport operators can assist their tenants by generally supporting the...
development of infrastructure and supply for alternative fuels at and near the airport. The focus
of the ACRP 02-23 project was to identify the possible benefits of various alternative fuels use
on improving local air quality. Airports operators can also work with other key stakeholders,
such as local governments, to further facilitate the implementation of alternative fuels. These
actions will result in the more widespread use of alternative fuel and, therefore, a greater
reduction in PM$_{2.5}$ emissions can be achieved than by the airport acting alone.

METHODOLOGY

This section describes the methodology developed to assess the principal sources of
PM$_{2.5}$ emissions and the contributions of these sources to local PM$_{2.5}$ concentrations, for each of
the five case study airports. The five airports are: Atlanta (ATL), Las Vegas (LAS), Philadelphia
(PHL), San Diego (SAN), and Manchester-Boston (MHT). The five case study airports were
identified at which to assess the impact of alternative fuels on PM$_{2.5}$ emissions and air pollution
concentrations based on data availability, willingness to participate, PM$_{2.5}$ non-attainment
designations, alternative fuel programs and the other evaluation criteria.

The principal components of the methodology included emissions inventories and
atmospheric dispersion modeling for both the base case and alternative fuel scenarios, which are
described in the following sections. A more detailed methodology is contained in the full report
(5).

Emissions Inventory for Base Case

Where available, airport-specific data were used to develop the emissions inventory and
dispersion modeling (EDMS) analyses for the base case based on previous airport specific
studies (6, 7, 8, 9, 10, 11). Specific airport data are required in the EDMS, including aircraft fleet
mix, airfield taxi times, GSE fleet mix and operating times, APU usage rates, runway use,
airfield operational profiles (quarter hourly, daily, and monthly), atmospheric mixing heights,
meteorological conditions, receptor locations, and background PM$_{2.5}$ concentrations.

EDMS is the FAA-required model for assessing airport-related air quality impacts.
Therefore, to estimate airport-related emissions, the airport data were used with FAA’s EDMS
(Version 5.1.2) (12) and its internal databases. This model version was the most recent available
at the initiation of the ACRP 02-23 project. Where airport-specific data were not available,
standard EDMS defaults or professional judgment were used.

Within each analysis year and for each airport, all the data elements were kept consistent.
For example, the analysis year for one particular airport was 2008, which includes 2008 data for
aircraft, road vehicles, meteorological conditions, and background PM$_{2.5}$ concentrations. These
analysis years and datasets were used for the base case and for the alternative fuels scenarios.

To enable more detailed emission factors to be generated and used (i.e., for the separation
of non-volatile and volatile emissions) and to enable comparison with previous studies at the
case study airports, EPA’s MOBILE6.2 model (all case study airports, except San Diego) (13)
and the California Air Resources Board (CARB) (14) Motor Vehicle Emission Factor Model
(EMFAC2007) model (used for San Diego) were used outside EDMS to generate emission
factors for road vehicles. The use of MOBILE6.2 outside of EDMS allowed region specific
vehicle mixes to be used (i.e., the proportion of different types of vehicles such as automobiles,
trucks, and vans). These emission factors were used as inputs to EDMS to enable generation of
emissions for roadways and parking facilities. It should be noted that the definition of “road
vehicles” varies between airports. For the purposes of the ACRP 02-23 project, the term referred
to vehicles that accessed the public roadways within the on-airport and external road networks. Therefore, this included some airport-related rolling stock. The boundary for road vehicles was dependent on the extent for which the data were available. In most cases, the original data used had been compiled for analysis in compliance with the National Environmental Policy Act (NEPA) for an airport development project and so conformed to the relevant boundary issues related to that particular airport (i.e., the spatial extent to which roadway sources were included).

NONROAD (15) (all case study airports expect San Diego) and OFFROAD2007 (16) (for San Diego) models were used to generate GSE emission factors. These models do not incorporate any separation of non-volatile and volatile emissions, so no separation of non-volatile and volatile GSE emissions was undertaken.

For PM$_{2.5}$ emissions from jet aircraft, the FAA has developed (with assistance from others and EPA concurrence) the FOA3a methodology, based on the ICAO agreed FOA3 (17, 18). Both the FOA3 and FOA3a methodologies are incorporated directly into EDMS, where FOA3a is used for U.S. airports.

The FOA3 and FOA3a methodologies use smoke number to estimate non-volatile emissions, and use hydrocarbon engine emission factors and sulfur fuel content to estimate volatile particulate emissions. In EDMS, the emissions are not reported separately for non-volatile and volatile PM$_{2.5}$. Therefore, the FOA3a equations were used to develop a methodology for separating out volatile PM$_{2.5}$ (i.e., into PM$_{2.5}$ originating from sulfur, hydrocarbons and lubricating oil) outside of EDMS. This also allowed separate scaling factors to be applied to the non-volatile, hydrocarbon and sulfur components of the jet aircraft emissions when calculating the alternative fuel emissions.

Road vehicle PM$_{2.5}$ emissions were partitioned into non-volatile and volatile particulate matter, based on the available information developed in the MOBILE6.2 and EMFAC emission factor models. Non-volatile and volatile are not separated out for gasoline vehicles in MOBILE. Therefore, volatile PM$_{2.5}$ emissions from road vehicles include organic carbon and sulfates (SO$_4$) from diesel.

**Emissions Inventory for Alternative Fuel Scenarios**

Alternative fuels were considered for those sources that contribute most to PM$_{2.5}$ emissions at airports. The selection process was heavily weighted towards the fuel’s potential to reduce PM$_{2.5}$ emissions, and limited to fuels with short-term (i.e., fewer than 10 years) commercial availability and those with available emission data. However, as part of the alternative fuel selection process a wide range of other criteria were also considered including:

- Availability of fuel emissions.
- Availability of new vehicles.
- Cost to convert existing vehicles.
- Whether the alternative fuel is a drop-in fuel (i.e., it can be used in an existing vehicle).
- Greenhouse gas (GHG) life-cycle emissions.
- Emission data source reliability.
- Cost of fuel compared with conventional.
- Cost of vehicles compared with conventional.
- Any additional infrastructure needed.
- Warranty validity.
The alternative fuel emission data also tend to be limited to those fuels that were available at the time of the study, albeit in low volumes, rather than emerging fuels. It should also be noted that any cost data available at present is based on a limited supply for some of the alternative fuels and therefore fuel cost could reduce considerably for these fuels in the future, depending on supply and demand (e.g. alternative jet fuels). Those fuels whose cost is more comparable to the conventional equivalent tend to be more established (e.g. CNG or low level bio-diesel blends (e.g. B5)). The Guidance Document (Appendix F) from ACRP 02-23 details the qualitative results of the analysis of cost and other variables.

In terms of road vehicles and GSE, the alternative fuels under consideration were: biodiesel, electricity (for which the analysis assumed zero emissions), ethanol, hydrogen (for which the analysis assumed zero emissions and, therefore, equivalent in terms of particulate matter to electricity), methanol (for which the analysis assumed zero emissions and, therefore, equivalent in terms of particulate matter to electricity, although there are likely to be some volatile emissions), and gas (e.g., CNG and LPG).

The majority of existing research into alternative aviation fuel has been related to jet fuel, which is used in turbine powered aircraft and APUs. There are two alternative fuels processes that are described by ASTM specification D7566-13 Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons (19). These two turbine fuels are described as Fischer-Tropsch hydروprocessed synthesized paraffinic kerosene (FT SPK, or FT in this paper) and synthesized paraffinic kerosene produced from hydroprocessed esters and fatty acids (HEFA SPK) are referred to as hydrotreated renewable jet fuel (HRJ) in this paper.

At the time of the study, only blends of up to 50/50 FT and 50/50 HRJ (i.e., up to 50% alternative fuel with at least 50% conventional fuel) (19) had been approved and it is likely that only blends will be approved in the short-term (e.g., fewer than 10 years). In the ACRP 02-23 project only the maximum (i.e., 50/50) blend allowed was considered. HRJ fuels were not analyzed separately in the ACRP 02-23 project due to lack of data at the time of study (20) as well as the similarity of the chemical structure of HRJ fuels to FT fuels, which were included.

The final selected case study alternative fuels and sources are shown in Table 1 along with the derived emission ratio used to scale the sources emissions for each scenarios. These emission ratios were derived from data obtained via an extensive literature review. The literature source for each derived emission ratio is also shown in Table 1.

**Table 1 Alternative Fuel Emission Factors Ratios and Literature Source**

<table>
<thead>
<tr>
<th>Fuel and Source type</th>
<th>Literature Source</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT (natural gas) jet aircraft main engines high thrust non-volatile emissions</td>
<td>Derived from black carbon emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine, NASA report on AAFEX (21)</td>
<td>0.41</td>
</tr>
<tr>
<td>FT (natural gas) jet aircraft main engines all thrust sulfur emissions</td>
<td>As neat FT fuels have negligible sulfur, it is assumed that a 50/50 FT blend would have 50% of the base fuel’s sulfur-related emissions</td>
<td>0.50</td>
</tr>
<tr>
<td>FT (natural gas) jet aircraft main engines high thrust volatile emissions</td>
<td>Derived from HC emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (22)</td>
<td>1.00</td>
</tr>
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<td>FT (natural gas) jet aircraft main engines low thrust non-volatile emissions</td>
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<td>Fuel and Source type</td>
<td>Literature Source</td>
<td>Ratio</td>
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<tr>
<td>main engines low thrust volatile emissions</td>
<td>and JP-8 in a high-bypass turbofan engine (22)</td>
<td></td>
</tr>
<tr>
<td>FT (coal) jet aircraft main engines high thrust non-volatile emissions</td>
<td>Derived from black carbon emissions for 50/50 blend and JP-8 in high-bypass turbofan engine, NASA report on AAFEX (21)</td>
<td>0.59</td>
</tr>
<tr>
<td>FT (coal) jet aircraft main engines all thrust sulfur emissions</td>
<td>As neat FT fuels have negligible sulfur, it is assumed that a 50/50 FT blend would have 50% of the base fuels sulfur-related emissions</td>
<td>0.50</td>
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<td>FT (coal) jet aircraft main engines high thrust volatile emissions</td>
<td>Derived from HC emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (22)</td>
<td>1.00</td>
</tr>
<tr>
<td>FT (coal) jet aircraft main engines low thrust non-volatile emissions</td>
<td>Derived from black carbon emissions for 50/50 blend and JP-8 in high-bypass turbofan engine, NASA report on AAFEX (21)</td>
<td>0.53</td>
</tr>
<tr>
<td>FT (coal) jet aircraft main engines low thrust volatile emissions</td>
<td>Derived from HC emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (22)</td>
<td>1.00</td>
</tr>
<tr>
<td>FT (coal) APU</td>
<td>Derived from APU black carbon high load emissions for 100% FT by assuming mixed 50/50 mix and JP-8 in NASA report on AAFEX (21)</td>
<td>0.56</td>
</tr>
<tr>
<td>FT (natural gas) APU</td>
<td>Assumed as per FT (coal) APU non-volatile emissions above</td>
<td>0.56</td>
</tr>
<tr>
<td>Electricity to replace some APU use</td>
<td>Assumes all APU run for 7 minutes based on EDMS defaults and FAA guidance (23) for APU use when the availability of pre-conditioned air and gate power is available</td>
<td>Ratio based on 7 minutes/base case time</td>
</tr>
<tr>
<td>91/96UL AvGas for piston-engine aircraft approach</td>
<td>Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (24)</td>
<td>0.025</td>
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<tr>
<td>91/96UL AvGas for piston-engine aircraft idle</td>
<td>Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (24)</td>
<td>0.020</td>
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<tr>
<td>91/96UL AvGas for piston-engine aircraft takeoff</td>
<td>Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (24)</td>
<td>0.030</td>
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<tr>
<td>91/96UL AvGas for piston-engine aircraft climb</td>
<td>Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (24)</td>
<td>0.029</td>
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<tr>
<td>FT (natural gas) Turboprop and turboshaft aircraft high thrust non-volatile emissions</td>
<td>Derived from black-carbon emissions for 50/50 blend and JP-8 in small turboshaft engine (25)</td>
<td>0.46</td>
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<tr>
<td>FT (natural gas) Turboprop and turboshaft aircraft low thrust non-volatile emissions</td>
<td>Derived from black-carbon emissions for 50/50 blend and JP-8 in small turboshaft engine (25)</td>
<td>0.53</td>
</tr>
<tr>
<td>Electric GSE</td>
<td>Used EDMS database files to replace GSE with electric equivalent where available (12)</td>
<td></td>
</tr>
<tr>
<td>Liquefied propane gas (LPG) GSE replacing diesel GSE</td>
<td>Used EDMS database files to replace diesel GSE with LPG equivalent where available (12)</td>
<td></td>
</tr>
<tr>
<td>Compressed natural gas (CNG) GSE replacing gasoline GSE</td>
<td>Used EDMS database files to replace gasoline GSE with CNG equivalent where available (12)</td>
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<tr>
<td>Fuel and Source type</td>
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<td>using EDMS</td>
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<td>databases</td>
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<tr>
<td>Gasoline with 10% ethanol blend (i.e., E10) in gasoline-fueled GSE</td>
<td>Based on E10 factor in AEA (26) for road vehicles</td>
<td>0.6</td>
</tr>
<tr>
<td>Diesel with 20% biodiesel blend (i.e., B20) in diesel-fueled GSE</td>
<td>Based on U.S. EPA (2002) exponential equation for biodiesel for road vehicles</td>
<td>0.880</td>
</tr>
<tr>
<td>100% biodiesel (i.e., B100) in diesel-fueled GSE</td>
<td>Based on U.S. EPA (27) exponential equation for biodiesel for road vehicles</td>
<td>0.528</td>
</tr>
<tr>
<td>Natural gas road vehicles to replace diesel</td>
<td>Based on running MOBILE with 100% natural gas for each airport (13)</td>
<td>Emissions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>recalculated</td>
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<tr>
<td></td>
<td></td>
<td>using MOBILE</td>
</tr>
<tr>
<td>Electric road vehicles</td>
<td>Electricity use has no direct PM$_{2.5}$ emissions</td>
<td>0</td>
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<td>Gasoline with 10% ethanol blend (i.e., E10) in gasoline-fueled road vehicles</td>
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Note: aircraft high thrust is defined as takeoff and climb, and low thrust as idle and approach.

In terms of road vehicles, the alternative fuel scenarios were only considered for on-airport roadways and parking (i.e., those under airport control and ownership). The base case and alternative fuel scenario emission calculations include some road vehicle emissions from vehicles not owned by the airport as it was not possible to separate the data for airport owned and other road vehicles (e.g., passenger travel to airport). Therefore, emission results were separated spatially according to whether the roadways were on-airport or off-airport. This approach maintains consistency with how airports are typically preparing their emissions inventories (for criteria pollutants and greenhouse gases), as some airports may have the ability to control vehicular use on some on-airport roadways. It is worth noting that, while not calculated due to lack of suitable data, road vehicles that drive on-airport are also likely to drive off-airport. Therefore changes in fuels used by these road vehicles would effect on-airport and off-airport emissions.

The ratio of emissions of the alternative fuel versus the base fuel for each relevant source and fuel type were calculated. The calculated ratios, show in Table 1, were used to scale the base case emissions to the alternative fuel scenario emissions, assuming all relevant emission sources use the alternative fuel.

It is not always feasible for all emission sources of a particular type to use one particular alternative fuel (e.g., not all diesel-fueled road vehicles will use B100). For each of the source and fuel combinations, a number of penetration options have been considered and the results calculated appropriately. For drop-in fuels that can be used in existing aircraft, such as FT (natural gas) or FT (coal), it is assumed that only one type of jet fuel would be available, as
airports are unlikely to have multiple jet fuels available. Therefore, it has been assumed that 100% of the aircraft fleet operating at these airports would be refueling on the alternative jet drop-in fuel. The 91/96UL AvGas fuel can, in theory, be used as a drop-in fuel in many piston-engine aircraft. However, not all piston-engine aircraft in the U.S. are certified to use it. As 91/96UL was only considered as an extension to the sensitivity analysis, a hypothetical 100% penetration was assumed.

The use of the EDMS databases to recalculate the emissions for some GSE scenarios allowed only the GSE with a relevant replacement to be considered (e.g., if no LPG alternative exists, it is not replaced). Therefore, a 100% uptake of the related GSE scenarios have been assumed to be feasible. Similarly, it is feasible that all gates at an airport could be fitted with pre-conditioned air and electric ground power, so the reduction in APU time was assigned a hypothetical 100% uptake.

For non-drop-in fuels (e.g., natural gas for road transport), a much lower penetration has been considered, based on different datasets (e.g., U.S. Energy Information Administration fuel use projections in 2020 (20)) and expert knowledge.

Atmospheric Dispersion Modeling Analysis
For the purpose of evaluating the potential impacts of airport emissions on local PM$_{2.5}$ concentrations in the vicinity of the case study airports, the ACRP 02-23 project used EDMS to generate the initial AERMOD input file. This input file was then edited to allow further source separation of the dispersion model results (i.e., by terminal area/concourse, aircraft mode, and internal and external roadways) and AERMOD (Version 09292) run outside of EDMS. As a theoretical example, the total concentration at a specific receptor may be 10 µg/m$^3$ and can be separated into individual source contributions of 2 µg/m$^3$ from aircraft engines, 4 µg/m$^3$ from Terminal A and 2 µg/m$^3$ from Terminal B (where terminal sources are related to GSE and APU), 1 µg/m$^3$ from roadways and 1 µg/m$^3$ from stationary sources. Furthermore, aircraft-related concentrations can be separated by operating mode (taxi, approach, takeoff and climb-out), which is related to aircraft thrust. The results were calculated for averaging periods that reflect the National Ambient Air Quality Standards (NAAQS) for PM$_{2.5}$ (i.e., the annual average and the 98th percentile of the 24-hour average).

Development of Impacts for Alternative Fuels
Separating out the different source contributions allows different scaling factors to be applied to each different source contribution. Taking the theoretical example, if Terminal A emissions (combined emissions from APU and GSE) are found to reduce by a factor of 0.5, then the contribution from Terminal A reduces from 4 µg/m$^3$ to 2 µg/m$^3$. If no other change in emissions is assumed, then the total concentration at the same receptor for this scenario is now 8 µg/m$^3$ (i.e., a reduction of 2 µg/m$^3$). Similarly, for each scenario, the relative change in emissions between the base case and the alternative fuel scenario (scenario/base) was applied to the relevant source contribution’s dispersion model results for each receptor point (i.e., individual locations). This enabled a scenario impact to be calculated for each receptor. Note that the GSE and APU emissions were dealt with on a terminal-by-terminal or concourse-by-concourse basis due to the emissions generated by EDMS being associated with more than one source group (i.e., GSE and APU) and to allow incorporation of the spatial distribution of these activities. Therefore, for each terminal/concourse, the scenario emissions (from APU and GSE) were calculated and the change relative the base case applied.
This methodology was applied to the base case annual and the eighth-highest 24-hour (i.e., 24-hour 98th percentile) impact results for each receptor. In theory, the impact of the eighth-highest 24-hour scenario impact could occur during a different hour (e.g., under different meteorological conditions) than the base case impact. However, for the study it was assumed to be the same hour.

The piston-engine and turboprop aircraft scenarios (which include turboshafts) have emission results only as part of the sensitivity analysis with an assumed 100% penetration. This is due to EDMS not incorporating the calculations of these two source types for PM$_{2.5}$. This enables those airports with a high proportion of turboprop, turboshaft, and piston-engine aircraft to assess the potential change in emissions associated with the use of alternative fuels for those aircraft types.

**BASE CASE RESULTS**

The purpose of the base case was to have a foundation against which to determine the benefits of the alternative fuels. However, the base case also provides valuable information that may assist airports with focusing their particulate matter emissions efforts.

The PM$_{2.5}$ emissions inventories developed for the five case study airports indicate that aircraft (taxi, approach, takeoff, and climb-out) contribute the greatest percentage of PM$_{2.5}$ emissions with GSE, APUs and road vehicle sources (on-airport and off-airport roadways, curbsides, and parking facilities) individually contributing to a much smaller extent generally for the case study airports. Stationary sources (e.g., boilers, generators, and fire training) generally contribute only a very small percentage to total airport PM$_{2.5}$ emissions. Aircraft-related emissions are largely a function of the number, types and sizes of aircraft operating at each airport, airfield taxi and delay time, and meteorological conditions. GSE emissions are mostly a function of equipment type, fuel type, engine size, equipment age, and operational hours. Diesel-fueled GSE tends to emit higher levels of PM$_{2.5}$ than gasoline-fueled GSE. APU emissions are a function of the presence of gate power and pre-conditioned air, both of which reduce APU operating times. Road vehicle emissions are determined by traffic volumes, travel distances, and emissions factors. In turn, road vehicle emissions factors are dependent on regional emissions controls, vehicle fleet mix, vehicle speed, and meteorological conditions.

The summary graph of EDMS-generated emissions, shown in Figure 1, depicts the emission sources at each airport in the study: Atlanta (ATL), Las Vegas (LAS), Philadelphia (PHL), San Diego (SAN), and Manchester-Boston (MHT). The emissions inventories developed for the five case study airports indicate that aircraft movements account for between 41% and 63% of total airport PM$_{2.5}$ emissions, depending on the airport. GSE accounts for between 5% and 37% of airport emissions. APUs account for between 9% and 22% of total airport PM$_{2.5}$ emissions, and road vehicles account for between 1% and 5% of total on-airport PM$_{2.5}$ emissions.
FIGURE 1 On-Airport Annual PM$_{2.5}$ Emissions Inventory by Source Category (kgs)

(a) The PHL analysis year was 2004 and included a disproportionate amount of diesel GSE compared to other airports, since 2004 PHL has implemented a number of alternative-fueled GSE replacements, and, therefore, the GSE analysis is not a true reflection of PHL in recent years.

EDMS does not typically include PM$_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no certification testing data or FAA accepted emission factors for those aircraft. Therefore, those aircraft were considered separately as part of the sensitivity analysis. Results from the sensitivity analysis indicate that, at the case study airports, aircraft emissions could be more than 17% higher than reported by EDMS. The issue of particulate matter emissions from piston-engine, turboprop, and turboshaft aircraft is more of an issue at smaller airports with a higher proportion of general aviation.

If the sensitivity analysis is discounted, aircraft at all case study airports are still the dominant source of PM$_{2.5}$ emissions. It should be noted that a large proportion of the aircraft emissions occur above the ground during the landing and takeoff (LTO) cycle and have little impact on ambient air pollution concentrations at a local level.

In terms of ambient air pollution, the results were calculated for averaging periods that reflect the National Ambient Air Quality Standards (NAAQS) for PM$_{2.5}$ (i.e., the annual average and the 98$^{th}$ percentile of the 24-hour average). Emissions from jet aircraft (taxi and takeoff), APU, GSE, roadways, and parking lots contribute most to ambient ground level PM$_{2.5}$ annual average concentrations at locations with high air pollution levels from the airports. A similar general conclusion can be drawn for the 24-hour 98$^{th}$ percentile results.

IMPACT OF ALTERNATIVE FUEL SCENARIOS AT CASE STUDY AIRPORTS

The alternative fuel scenarios EDMS-generated results for each isolated scenario were calculated in terms of percentage reductions for the annual average and 24-hour 98$^{th}$ percentile. However, this paper only discusses key results for the total on-airport emissions and the area in which the air quality impact from the airport is below the threshold level is referred to as the influence area. The threshold level for the annual average is 0.3 µg/m$^3$. 
Figure 2 summarizes EDMS-generated emission reductions totals for all on-airport emissions, based on the results for the case study airports, for each of the alternative fuel scenarios for the annual average. Figure 2 shows that the largest emission reductions are provided by the following scenarios (listed in descending order):

- 100% of aircraft and APU use drop-in fuels (i.e., 50% blends of FT jet fuels from either coal or gas).
- Replacing a 100% of GSE with available electric, LPG or CNG equivalents, especially diesel-fueled GSE.
- Replacing 100% of diesel with B100 in GSE (though it should be noted that this could have implications for GSE in terms of engine warranty).
- Reducing APU use by providing electric ground power and pre-conditioned air at 100% of gates.
- Emission reductions for other scenarios are relatively small.

To demonstrate the impact on localized airport air quality, Figure 3 summarizes the change in influence area for annual air pollution impacts (again, for the EDMS-generated results and based on the case study airports). Further results for the other key indices are contained in the full report (5). As GSE emissions can have a greater influence on localized air quality than other sources, the alternative fuel scenarios for GSE had the greatest effect on the airport influence area concentrations. Figure 3 shows that the largest reductions in annual average influence area are provided by the following scenarios (listed in descending order):

- Replacing a 100% of GSE with available electric equivalents.
- 100% of aircraft and APU use drop-in fuels (i.e., 50% blend of FT jet fuels from either coal or gas).
- Replacing a 100% of GSE with available LPG or CNG equivalents, especially diesel-fueled GSE.
- Reducing APU use by providing electrical ground power and pre-conditioned air at 100% of gates.
- Replacing 100% of diesel with B100 in GSE (though it should be noted that this could have implications for GSE in terms of warranty).
- The concentration reductions for other scenarios are relatively small.
FIGURE 2 Alternative Fuel Scenarios versus Base Case – Percentage Change of Total Airport Emissions

Note: The implied increase in emissions for the “100% CNG GSE replacing gasoline GSE, where model available” scenario is a theoretical modeling output related to the emission factor source data used, and is not likely to be observed in actual practice.
FIGURE 3 Alternative Fuel Scenarios versus Base Case – Percentage Change of Annual Influence Area

Note: The implied increase in emissions for the “100% CNG GSE replacing gasoline GSE, where model available” scenario is a theoretical modeling output related to the emission factor source data used, and is not likely to be observed in actual practice.
As EDMS does not typically include PM$_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft, these aircraft types were considered separately as part of the sensitivity analysis. The alternative fuel scenarios included FT (natural gas) jet fuel for turboprop and turboshaft aircraft and 91/96UL AvGas for piston-engine aircraft. For the five case study airports, the emission reductions for the specific aircraft type (compared with the base case) were around 50% reduction when a blend of 50% FT (natural gas) is used in turboprop (including turboshaft) aircraft and an above 90% reduction when 91/96UL AvGas is used in piston-engine aircraft.

CONCLUSIONS
In addition to the results discussed, the four key conclusions are summarized. First, as HRJ jet fuels have a similar chemical structure to FT fuels, the findings for FT jet fuels should be considered broadly applicable to HRJ jet fuels as well. Second, the findings for alternative fuel use in jet aircraft could be considered broadly applicable to turboprop and turboshaft aircraft. Third, the impact of gate-related emissions (i.e., mainly those from APU and GSE) have a limited impact on air quality away from the gate areas compared to other sources where the emissions are spread over a wider area, such as aircraft and road vehicle sources. Finally, fourth, for GSE and road vehicles the best PM$_{2.5}$ emission reductions are gained when (in increasing order): gasoline, CNG, LPG, or electric vehicles replace diesel.

It should also be noted that the resulting spreadsheet tool (5) can be used by airports to experiment with different combinations of scenarios.

It should also be noted, as discussed in the background section, that alternative fuels are only one route to reducing airport-related PM$_{2.5}$ emissions. Other strategies to address local air quality concerns close to airports include reducing delay and improving operational efficiency of mobile sources (3, 4).

Various opportunities exist for alternative fuels to be used at airports (e.g., buildings, aircraft, and ground vehicles in airport controlled areas). However, many of the main sources of airport-related PM$_{2.5}$ emissions (and the primary potential users of alternative fuels) are not under the direct control of airport operators in terms of the emission sources. Airport operators can assist their tenants by generally supporting the development of infrastructure and supply for alternative fuels at and near the airport. Airports operators can also work with other key stakeholders, such as local governments, to further facilitate the implementation of alternative fuels. These actions will result in the more widespread use of alternative fuel and, therefore, a greater reduction in PM$_{2.5}$ emissions can be achieved than by the airport acting alone.

Airports should also consider that any cost data available at present is based on a limited supply for some of the alternative fuels and therefore fuel cost could reduce considerably for these fuels in the future, depending on supply and demand (e.g. alternative jet fuels). Those fuels whose cost is more comparable to the conventional equivalent tend to be more established (e.g. CNG or low level bio-diesel blends (e.g. B5)).

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