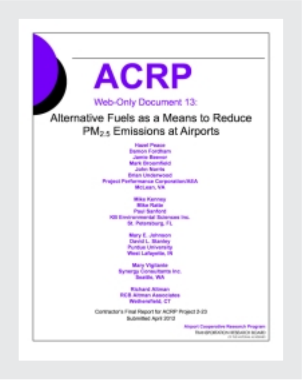

Alternative Fuels as a Means to Reduce PM2.5 Emissions at Airports

DETAILS

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

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Dr. Hazel Peace, Knowledge Leader for Aviation at PPC/AEA, was the Project Technical Director and co-Principal Investigator and is the main author of the report. Damon Fordham of PPC/AEA is co-Principal Investigator and Project Manager for the overall research effort. Contributing authors of the report are Dr. Mark Broomfield, Jamie Beevor, Dr. John Norris, and Dr. Brian Underwood of PPC/AEA; Mike Kenney, Mike Ratte, and Paul Sanford of KB Environmental Sciences Inc.; Dr. Mary E. Johnson and David L. Stanley of Purdue University; Mary Vigilante of Synergy Consultants Inc.; and Richard Altman.

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ABSTRACT

This report documents the findings of the ACRP 02-23 project 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. 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.

EXECUTIVE SUMMARY

This report presents the findings of the ACRP 02-23 project undertaken to investigate the impact that alternative fuels could have on reducing emissions and ambient air pollution concentrations of fine particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) at airports. The ACRP 02-23 project consisted of reviewing published studies concerning particulate matter emissions and then modeling the effects of various alternative fuels on actual case study airports. The case study airports reflected locations where existing information was available to facilitate this research and represented different activity levels, meteorology, climate, geography, and demographics. Using these case study airports as a basis, an evaluation was then conducted of the effects of alternative fuels on particulate matter emissions from airport-related sources.

Literature Review

A comprehensive literature review of information and data from over 200 national and international references was undertaken. This literature review, as reported in Chapter 2, was used to inform the data collection requirements for the ACRP 02-23 project and to underpin the development of the methodology.

Only a small number of $PM_{2.5}$ measurement (monitoring) campaigns have been carried out at airports. These measurement efforts indicate that while airport sources may be contributing to local emissions, the overall impact diminishes rapidly as distance from sources increases. With respect to aircraft emissions, the literature review found that very few aircraft have reliable particulate matter emission data. Due to these data limitations, First-Order Approximation (FOA) methods were developed by ICAO/CAEP to enable particulate matter emissions for aircraft to be calculated.

A significant amount of research has been conducted into the use of alternative aircraft fuels:

- Commercial airlines have tested alternative fuels blended with Jet A-1 on a limited number of overseas flights.
- The entire fleet of U.S. Air Force (USAF) aircraft is expected to be certified to use blended alternative fuels by 2016.
- Large reductions in aircraft PM2.5 emissions are possible with the newer alternative fuels that are suitable for aircraft use.

A variety of different alternative fuels can be used for ground support equipment (GSE), and the Federal Aviation Administration (FAA) Emissions and Dispersion Modeling System (EDMS) already includes emissions factors for GSE operating on liquefied petroleum gas (LPG), compressed natural gas (CNG), and electricity. Possible alternative fuels for road vehicles include gasoline and ethanol blends and fossil diesel and biodiesel blends.

Case Study Airports

In parallel to the literature review, a review of data availability and willingness of U.S. airports to participate as case studies was undertaken. As discussed in Chapter 3, five case study airports were selected for inclusion in the ACRP 02-23 project:

- Hartsfield-Jackson Atlanta International Airport (ATL)

- Las Vegas McCarran International Airport (LAS)
- Manchester-Boston Regional Airport (MHT)
- Philadelphia International Airport (PHL)
- San Diego International Airport (SAN)

Identifying Suitable Alternative Fuels

The alternative fuels for the ACRP 02-23 project were selected using a multi-criterion screening process, which is outlined and discussed further in Chapter 4. A wide range of criteria were considered including:

- Change in $PM_{2.5}$ emissions
- Availability of fuel
- 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 issues

Alternative fuels were considered for those sources that contribute most to $PM_{2.5}$ emissions at airports. The selection process was heavily weighted toward 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. For example, hydroprocessed renewable jet fuel (HRJ) was initially considered, but was discounted due to the lack of appropriate emission data at the time of the ACRP 02-23 project.

The final selected case study alternative fuels and sources were:

- Fischer-Tropsch (FT) (natural gas) aircraft
- FT (coal) aircraft
- 91/96UL AvGas for piston-engine aircraft
- FT (natural gas) APU
- FT (coal) APU
- Electricity to replace some APU use
- Electric GSE
- Liquefied propane gas (LPG) GSE replacing diesel GSE
- Compressed natural gas (CNG) GSE replacing gasoline GSE
- CNG GSE replacing diesel GSE
- Gasoline with 10% ethanol blend (i.e., E10) in gasoline-fueled GSE
- Diesel with 20% biodiesel blend (i.e., B20) in diesel-fueled GSE
- 100% biodiesel (i.e., B100) in diesel-fueled GSE
- Natural gas road vehicles to replace diesel road vehicles
- Electric road vehicles

- E10 in gasoline-fueled road vehicles
- B20 in diesel-fueled road vehicles
- B100 in diesel-fueled road vehicles

Methodology

A methodology to establish the base case $PM_{2.5}$ emissions and local $PM_{2.5}$ pollutant concentrations at each case study airport was developed. This methodology is discussed in detail in Chapter 5. The alternative fuel scenarios were then generated to assess the relative change on a number of key indices representing the impact that each alternative fuel and source combination would have on $PM_{2.5}$ emissions and local $PM_{2.5}$ pollutant concentrations at each case study airport. Additional emissions from alternative fuel distribution emissions (e.g., tanker trucks carrying alternative fuels) were not included in the analysis. Instead, only the relative change in the emissions for the same source activity levels was considered.

In terms of road vehicles, the alternative fuel scenarios were considered only for on-airport roadways and parking (i.e., those under airport control and ownership).

It is not always feasible for all emission sources of a particular type to use one particular alternative fuel. Therefore, penetration factors were applied to scale the emissions for each alternative fuel and source type.

EDMS does not typically include $PM_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no FAA accepted emission factors for these aircraft. During the development of the emissions calculation methodology used in the ACRP 02-23 project, it was found that more than 50% of the aircraft operating at some of the case study airports were of types for which EDMS does not estimate $PM_{2.5}$ emissions. For this reason, a number of alternative methodologies were used to estimate emissions for these types of aircraft. A sensitivity analysis of the impacts of these methodologies upon aircraft emissions was conducted. For those aircraft where there is no appropriate alternative calculation methodology, emissions were scaled based on the average emissions for that aircraft size.

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 base case results are discussed further in Chapter 6 and Appendix E.

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 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 speed, and meteorological conditions.

The summary graph of EDMS-generated emissions, shown in Figure 1, depicts the emission sources at each airport. 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.

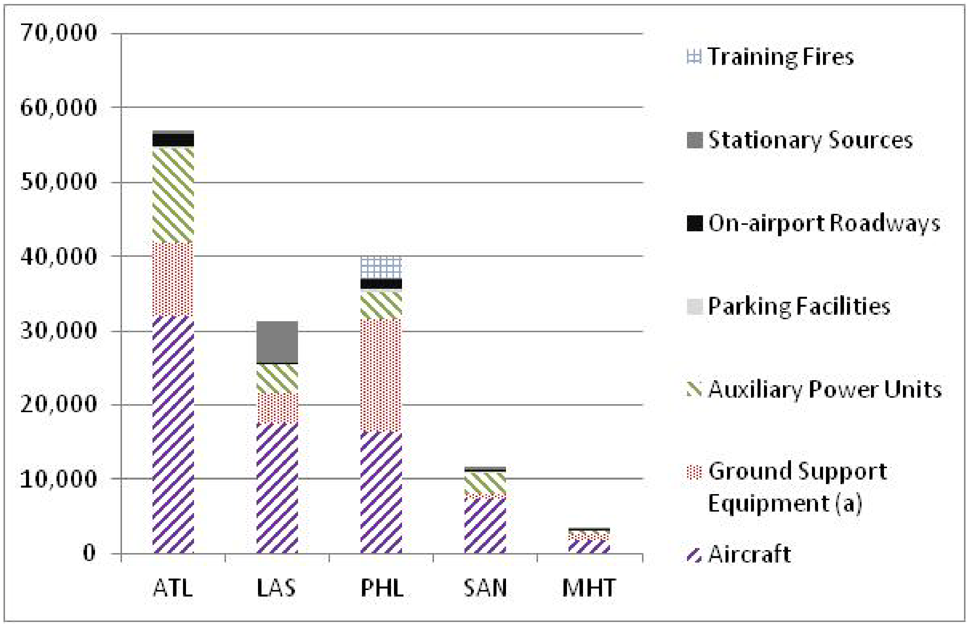


Figure 1 – On-Airport Annual $PM_{2.5}$ Emissions Inventory by Source Category (kgs)

(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 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 98th 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 98th percentile results.

Impact of Alternative Fuel Scenarios at Case Study Airports

The alternative fuel scenarios are presented in Chapter 6 for the EDMS-generated results for each isolated scenario, in terms of percentage reductions for the annual average and 24-hour 98th percentile, for the following key indices:

- The total on-airport emissions.
- The airport impact concentration at the location of the maximum airport impact concentration in the base case.
- The maximum distance from the airport to a threshold airport impact concentration level, termed the Radius of Influence (ROI). The ROI is defined as the distance that extends from the source (in this case, the airport reference point) to the farthest receptor distance at which the source has a concentration greater than a specific threshold for a given pollutant. The threshold level for the annual average is 0.3 $\mu g/m^3$ and for the 24-hour 98th percentile it is 1.2$\mu g/m^3$.
- 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 $\mu g/m^3$ and for the 24-hour 98th percentile it is 1.2$\mu g/m^3$.

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 (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). 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 (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.

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.
- Above 90% reduction when 91/96UL AvGas is used in piston-engine aircraft.

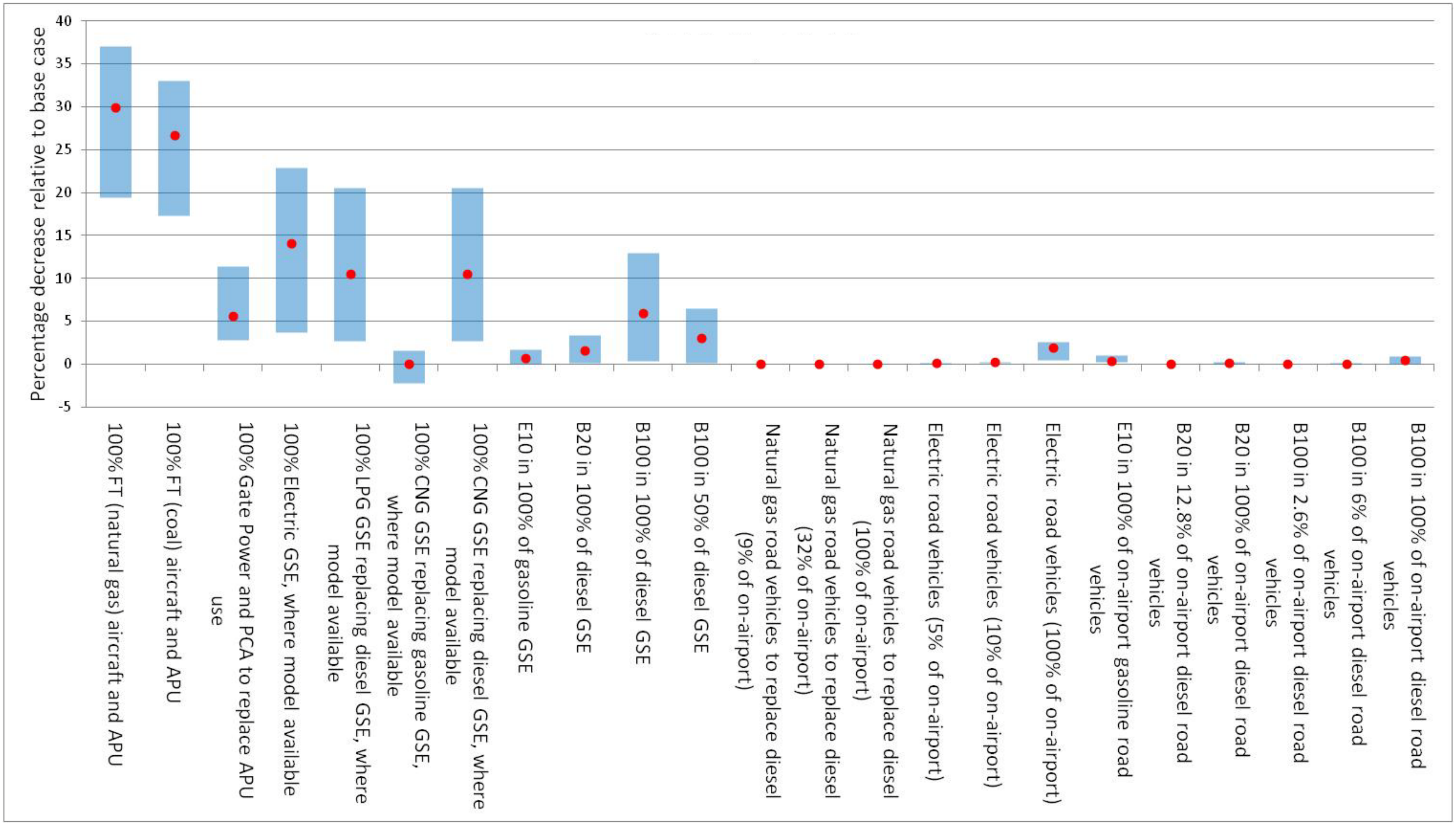


Figure 2 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Total Airport Emissions

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.

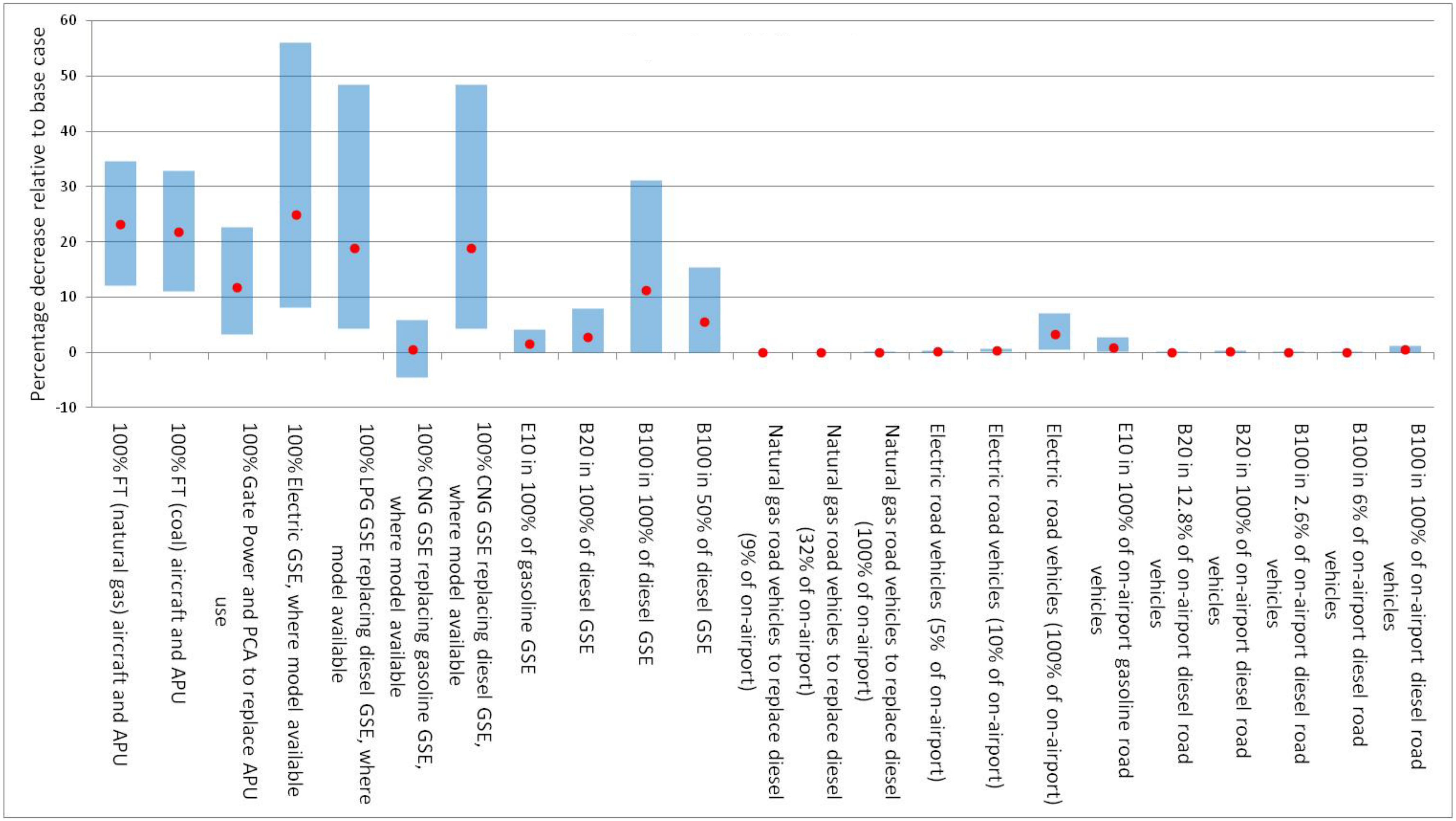


Figure 3 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Annual Influence Area

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.

Conclusions

In addition to the results discussed previously the key conclusions are summarized below:

- 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.
- The findings for alternative fuel use in jet aircraft could be considered broadly applicable to turboprop and turboshaft aircraft.
- 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.
- 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.

Recommendations

The study of air pollution and, in particular, $PM_{2.5}$ around airports is not a static subject. During the course of the ACRP 02-23 project, a number of future sources of information, model developments and improvements were apparent. Therefore, the following recommendations for future study have been made based on this information:

- The NASA AAFEX report was the primary source for the jet aircraft main engine and APU alternative fuel emission data. This NASA study was based on one jet engine and one APU. Further study is needed to understand the variation that the use of alternative fuels could have on other turbine engine types.
- Various alternative fuels for aircraft and non-aircraft sources of $PM_{2.5}$ were considered and discarded for a variety of reasons. One of the primary reasons was lack of suitable $PM_{2.5}$ emission data. As such, the ACRP 02-23 project could be updated when further, appropriate, alternative fuel $PM_{2.5}$ emissions are available (e.g., from the various PARTNER and AAFEX II projects and the resulting database of $PM_{2.5}$ emission factors and from the various ACRP projects aimed at refining APU, brake and tire wear, and GSE emissions).
- The FAA is in the process of developing the Aviation Environmental Design Tool (AEDT) combined noise and air pollution model, which will replace the FAA's EDMS in the future. Similarly, EDMS incorporates MOBILE6.2, which has been superseded by the EPA's MOVES model. The MOVES model is being developed to incorporate road and nonroad sources, as well as a number of alternative fuels. As such, it would be worth repeating the ACRP 02-23 research with these two models when they are complete.
- Further research is needed to quantify the impact that specific types of biofuel (by feedstock, blend and engine type) will have on primary and volatile (i.e., "secondary") particulate matter emissions.

CHAPTER 1:

BACKGROUND

AIRPORTS AND AIR QUALITY

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. Concerns about air quality may impact the review and approval process for airport development projects. Local air quality is affected by air emissions of pollutants associated with sources at an individual airport. Global air quality generally refers to greenhouse gases and their climate change. For local air quality, the National Ambient Air Quality Standards (NAAQS) criteria pollutants include ozone (with the associated precursors volatile organic compound (VOC) and oxides of nitrogen (NOx) emissions), carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), course particulate matter (PM_{10}), fine particulate matter ($PM_{2.5}$), and lead (Pb). This report focuses on the emissions and local impacts of $PM_{2.5}$ in the context of airports.

Particulate matter is generally designated as PM_{10} (coarse), $PM_{2.5}$ (fine), and $PM_{0.1}$ (ultra-fine), where the number refers to the particle size (aerodynamic diameter that characterizes the size distribution of the aerosol fraction). The smaller the particle, the more likely it is that it will become lodged in the lungs and, therefore, cause health problems. The smallest particle size for which there is a U.S. Environmental Protection Agency (EPA) health-related standard is $PM_{2.5}$. Those standards have driven data collection for $PM_{2.5}$. Therefore, emissions measurements and ambient concentration data for $PM_{2.5}$ are available. There is now increasing concern about ultra-fine particles ($PM_{0.1}$), but because an ambient standard has not been set, there is less understanding in the scientific community and data are not as available.

Recent studies of emissions from aircraft jet engines show that $PM_{0.1}$ may be the dominant particulate matter emissions of concern in contrast to other sources. However, as discussed previously, for $PM_{0.1}$, there are no ambient air quality standards and very little data that can be used to underpin particulate matter and research into alternative fuels. Therefore, this Airport Cooperative Research Program (ACRP) research project, ACRP 02-23, has concentrated on $PM_{2.5}$, while acknowledging that $PM_{0.1}$ emissions are also of health concern. Alternative fuels that have beneficial impacts with regard to $PM_{2.5}$ emissions are also likely to contribute to reductions in $PM_{0.1}$ emissions.

$PM_{2.5}$ in the atmosphere arises from primary and secondary sources. For this research, primary sources are considered to result in the direct emission of particulate matter into the atmosphere and typically include sources related to fuel combustion. Primary particulate matter from fuel combustion can be measured at the point of emission (e.g., exhaust, stack exit), and includes volatile and non-volatile components. Sometimes, the volatile components of particulate matter emissions are referred to as secondary emissions, but they should not be confused with secondary atmospheric particulate matter. Secondary atmospheric particulate matter sources include chemical reactions with other pollutants (e.g., SO_2, NO_x, and ammonia) in the atmosphere to form solid sulfates and nitrates, as well as the oxidation of non-methane VOCs (NMVOCs) to form organic aerosols. These interactions may take minutes or days, and the effects can be seen hundreds of miles from the point of release.

Due to the potential confusion over the term "secondary particulate matter," the following definitions are used for the ACRP 02-23 project:

- **Non-volatile emissions**: Sometimes referred to as "primary emissions," these are mostly carbon-related emissions (soot).
- **Non-fuel primary emissions**: These relate to brake wear, tire wear and dust type emissions, and are not the primary concern of the ACRP 02-23 project (which is related to fuel use).
- **Volatile emissions**: Sometimes referred to as "secondary emissions," these are particulate matter "emissions" that form close to the point of release for a particular source and are typically related to the sulfur and hydrocarbon content of the fuel.
- **Secondary particulate matter**: This refers to secondary atmospheric particulate matter unless explicitly stated as referring to an emission.

PARTICULATE MATTER AMBIENT STANDARDS

Through the Federal Clean Air Act (CAA), the EPA has promulgated NAAQS for several criteria air pollutants. The primary standards are ambient (outdoor) levels of pollutants established to protect public health. Secondary standards are levels set to protect the public welfare and the environment (e.g., visibility, vegetation, deterioration of buildings). On a nationwide basis, the current 24-hour NAAQS for $PM_{2.5}$ is 35 $\mu g/m^3$ and the annual standard is 15 $\mu g/m^3$. Table 1 summarizes the current NAAQS for $PM_{2.5}$. It should be noted that the EPA is making recommendations to reduce the $PM_{2.5}$ NAAQS (U.S. EPA, 2011b).

Table 1 – National Ambient Air Quality Standards for $PM_{2.5}$

Pollutant	Primary Standards		Secondary Standards	
	Level	**Averaging Time**	**Level**	**Averaging Time**
Fine Particulate Matter ($PM_{2.5}$)	15 $\mu g/m^3$	Annual* (arithmetic mean)	Same as Primary Standards	
	35 $\mu g/m^3$	24-hour†	Same as Primary Standards	

* To attain this standard, the 3 year average of the weighted annual mean $PM_{2.5}$ concentrations from single or multiple community-oriented monitors must not exceed 15 $\mu g/m^3$

† To attain this standard, the 3 year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 $\mu g/m^3$ (effective December 17, 2006)

Source: U.S. EPA, 2011a

The "averaging time" for each NAAQS is based on the time over which sensitive members of the population would be affected detrimentally (e.g., 1 hour, 8 hours, 24-hours, and annual average). Averaging times depend on the pollutant's physical and chemical characteristics as well as the weight of toxicological and epidemiological evidence supporting the NAAQS. Notably, individual states are allowed to supplement the NAAQS with additional or more stringent state level, air quality standards.

NON-ATTAINMENT AREAS

The EPA requires that state or regional air quality agencies install and maintain ambient air monitoring networks to identify areas in the U.S. that are in violation of the NAAQS. A geographic area possessing ambient concentrations of an EPA regulated pollutant 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". As the $PM_{2.5}$ standard is relatively new, no areas have been re-designated as attainment, but some are subject to a maintenance plan due to a recent past exceedance.

Figure 4 and Figure 5 (U.S. EPA, 2011c) show areas of the U.S. currently in violation of the annual and 24-hour $PM_{2.5}$ standards, respectively, based on recent air monitoring data (U.S. EPA, 2010b).

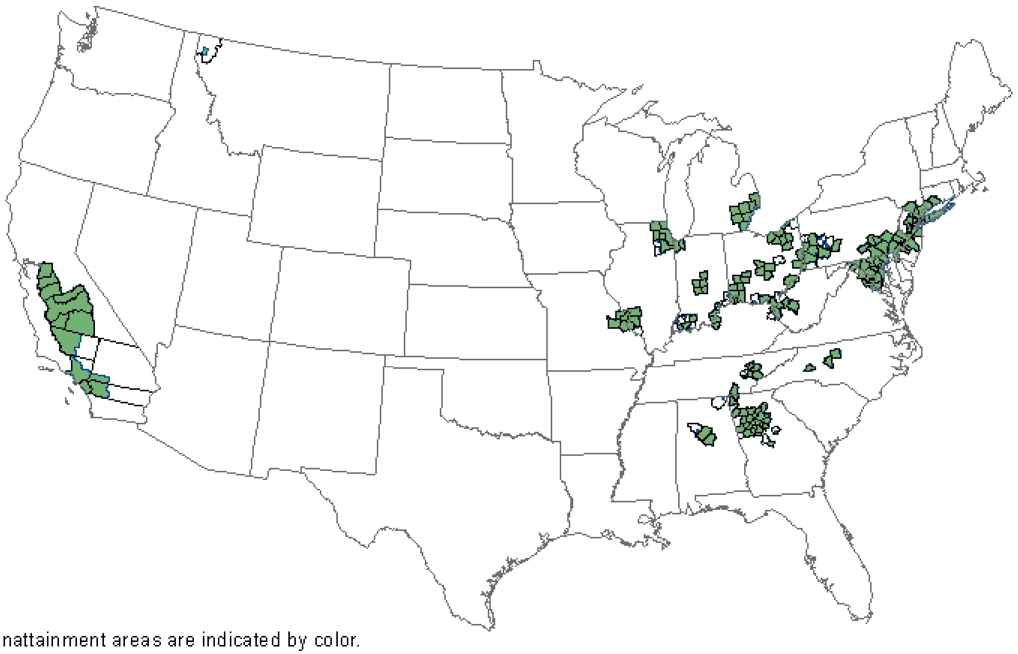
More than 50 commercial service airports in the U.S. are located in $PM_{2.5}$ non-attainment areas. Over time, additional locations may be subject to $PM_{2.5}$ non-attainment designations because the standards are often tightened following the NAAQS review every five years. Airport development projects located in non-attainment or maintenance areas must be shown to conform to the applicable state's plan for compliance with the Clean Air Act before they can be approved by the Federal Aviation Administration (FAA). The general conformity regulations specify the steps for considering emissions. The first step is to determine the "applicability" of the regulation. It involves comparing project-related emissions to a de minimis threshold. A de minimis threshold of 100 tons per year is defined for $PM_{2.5}$. If emissions exceed this threshold, a full determination is required, possibly with consideration of mitigation options.

Of note, airports tend to contribute only a small amount to an area's overall emissions. Table 2 presents the airport (from Chapter 6) and metropolitan statistical area (MSA) (U.S. EPA, 2002a) emissions for the airports included in the ACRP 02-23 project.

Table 2 – Airport and Regional Emissions

Airport	Airport in non-attainment Area?	MSA $PM_{2.5}$ Emissions (Tons), A	Airport $PM_{2.5}$ emissions (Tons), B	Ratio of B/A
Hartsfield-Jackson Atlanta International Airport (ATL)	Yes	45,800	63.0	0.0014
Las Vegas McCarran International Airport (LAS)	No	12,701	34.6	0.0027
Philadelphia International Airport (PHL)	Yes	18,084	44.3	0.0024
San Diego International Airport (SAN)	No	17,804	13.1	0.0007
Manchester-Boston Regional Airport (MHT)	No	9,527	3.7	0.0004

Source: MSA data (U.S. EPA, 2002a).

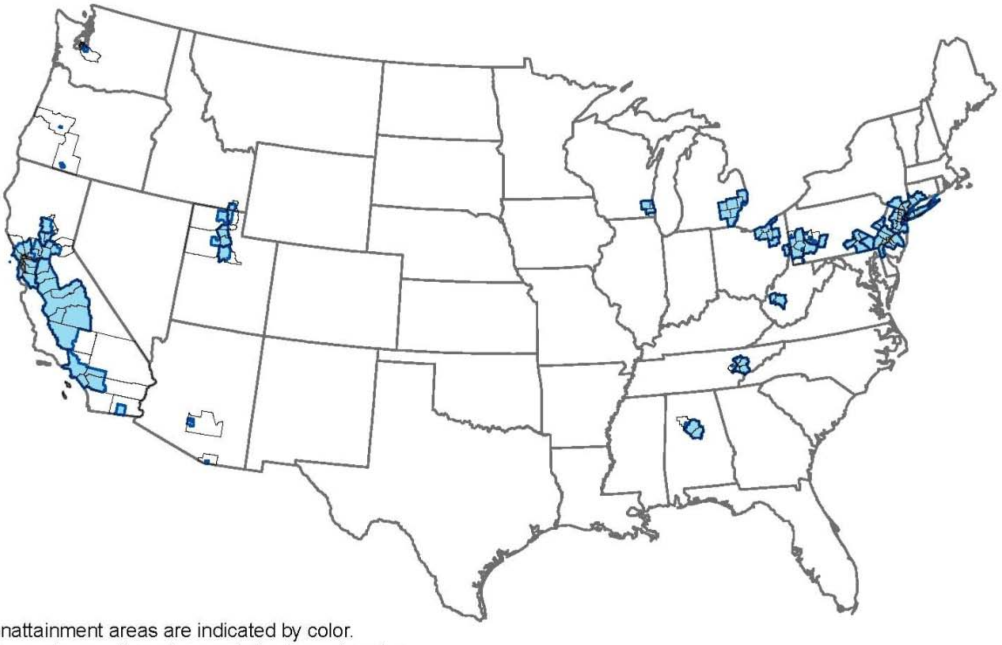


Nonattainment areas are indicated by color.
When only a portion of a county is shown in color,
it indicates that only that part of the county is within
a nonattainment area boundary.

12/2010

Figure 4 – $PM_{2.5}$ Non-Attainment Areas as of December 2010 (Annual Standard)

Source: Green Book Non-attainment Areas for Criteria Pollutants, U.S. EPA (2011c)



Nonattainment areas are indicated by color.
When only a portion of a county is shown in color,
it indicates that only that part of the county is within
a nonattainment area boundary.

4/2011

Figure 5 – $PM_{2.5}$ Non-Attainment Areas as of April 2011 (24-hour Standard)

Source: Green Book Non-attainment Areas for Criteria Pollutants, U.S. EPA (2011c)

IMPLICATIONS FOR AIRPORTS

Proposed improvement projects at Los Angeles International and Philadelphia International airports are facing heightened agency review because of the potential impacts of added airport capacity to local and regional $PM_{2.5}$ air quality. Other airports around the country (e.g., Chicago O'Hare International, Seattle-Tacoma International, George Bush Intercontinental/Houston) have experienced similar public concerns about the potential health effects associated with the combustion of jet fuel, principally due to emissions-related to particulate matter. Expansion projects at other airports to address capacity needs will likely face increased pressure to consider the impacts of particulate matter and emissions of related local pollutants. One of the ways in which airports can assist in reducing $PM_{2.5}$ impacts is by increasing the availability and use of alternative fuels. Other strategies to address local air quality concerns close to airports include reducing delay and improving operational efficiency of mobile sources (BAA, 2007; GAL, 2009; AEA, 2009).

AIRPORTS AND ALTERNATIVE FUELS

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) (which, in the ACRP 02-23 project, are defined as vehicles and equipment used on the airfield that support aircraft operations that are often controlled by airlines, other fixed base operators, as well as airports) and aircraft. Many airports around the country are developing emission reduction plans identifying actions that can be undertaken to reduce airport-related emissions. Airport operators can assist their tenants by generally supporting the development of infrastructure and supply for alternative fuel 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.

CHAPTER 2:

LITERATURE REVIEW

This chapter presents a summary of key subject areas researched as part of the literature review, with the intention of providing a general context of the information gathered. The full literature review findings are described in Appendix A. The literature review was undertaken primarily to underpin the development of the calculation methodology and to inform the ACRP 02-23 project's data collection requirements. This chapter includes summary information on the following:

- Relevant emissions inventory and dispersion models
- Ambient $PM_{2.5}$ monitoring studies at airports
- Aircraft and auxiliary power unit (APU) emissions, including the related alternative fuels
- GSE emissions, including the related alternative fuels
- Road vehicle emissions, including the related alternative fuels
- Other sources of emissions, including the related alternative fuels
- Dispersion modeling in the context of U.S. airports

RELEVANT EMISSIONS INVENTORY AND DISPERSION MODELS

A number of models are available to evaluate air pollutant emissions associated with various sources. However, FAA evaluations under the National Environmental Policy Act (NEPA) require the use of Emissions and Dispersion Modeling System (EDMS) for all airport sources. EDMS has also been accepted for use by the EPA. Incorporated into EDMS are various EPA models including AERMOD for dispersion modeling, MOBILE for road vehicle emission factors and NONROAD for GSE emission factors. The EPA's Motor Vehicle Emissions Simulator (MOVES) model is relatively new and is intended to capture all surface mobile sources (e.g., road vehicles, ground access vehicles). However, it is not incorporated into EDMS.

The literature review informed the development of the methodology and the use of various models. To enable the results of the ACRP 02-23 project to be used in the airport setting, modeling performed for the ACRP 02-23 project was undertaken primarily using EDMS version 5.1.2 and its related models. To enable separation of non-volatile and volatile emissions, detailed emission factors were generated in EPA's MOBILE6.2 model for all the case study airports, except San Diego International Airport (SAN). The California Air Resources Board's (CARB) EMFAC2007 and OFFROAD2007 models were used for SAN due to its location in California where these models are typically used. The emission factors were then fed back into EDMS to enable emissions of road vehicles to be generated. 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 modeled results (i.e., by terminal area/concourse, aircraft mode, and internal and external roadways) and AERMOD (Version 09292) run outside of EDMS. The use of these models is discussed further in Chapter 5 and Appendix D.

AMBIENT $PM_{2.5}$ MONITORING STUDIES AT AIRPORTS

A small number of $PM_{2.5}$ air monitoring studies have been carried out at airports across the U.S. (SCAQMD, 2000a, 2000b; Fanning et al., 2007; Westerdahl et al., 2008; Hu et al., 2009; Massport, 2010; ENVIRON, 2008; RI DEM, 2008; Dodson et al., 2009 and BCAA, 2006). The overarching goal of these studies was to apportion airport contributions to $PM_{2.5}$ and assess the potential impact of $PM_{2.5}$ on nearby public areas. The findings of these studies appear to indicate that, while sources at airports may be contributing to local emissions, the overall impact diminishes rapidly as the distance from key emission sources increases. Furthermore, non-airport sources (e.g., road vehicles) may have more impact on local air quality depending on the relative location of the source and the monitoring location.

In developing a methodology to select case study airports, it was noted that $PM_{2.5}$ measurements should be available near the case study airports. Ideally, case study airports would have detailed monitoring data at a number of locations close to the airport to allow for cross comparison between monitored and modeled data. However, very little detailed data exist. Consequently, for the ACRP 02-23 project, the monitoring data that were available are used only to estimate background (or non-modeled) concentrations, enabling total concentrations to be calculated.

AIRCRAFT AND APU EMISSIONS

An aircraft's engine is its main propulsion unit and comes in four main types—jet turbines, turbofans, turboprops (including turboshaft), and pistons. In addition to the main engines, many larger aircraft also have an APU that is used for support purposes, such as engine starting and air-conditioning. As very few aircraft have reliable particulate matter emission factors, the first-order approximation (FOA) was developed by ICAO/CAEP to enable calculation of particulate matter emissions from aircraft-based on available data. There are two current and generally similar versions of FOA—FOA3 and FOA3a (U.S. airports only). FOA3a includes default U.S. agreed factors for sulfur content and the inclusion of emissions-related to lubrication oil, whereas FOA3 allows for a number of different sulfur fuel contents to be assumed and does not include a defined methodology for calculating emissions-related to lubrication oil.

The literature review examined the derivation of FOA3a and the underlying FOA3 as approved by the International Civil Aviation Organization (ICAO) (ICAO, 2011 and 2007), which are used to estimate non-volatile and volatile particulate matter from jet turbine and turbofan aircraft main engines. The review also looked at the historical development of FOA3 and the need for the development of particulate matter engine certification.

EDMS was used to quantify emissions from aircraft main engines and APUs. FOA3a was also used in the ACRP 02-23 project to separate out the EDMS-generated volatile and non-volatile particulate matter emissions, for jet aircraft main engines, as discussed in Chapter 5 and Appendix D. No methodology was found to separate out other aircraft emissions (i.e., APU, and turboprop, turboshaft and piston-engine aircraft) into volatile and non-volatile. Particulate matter emission factors were sourced separately for turboprop, turboshaft, and piston-engine aircraft since EDMS does not typically calculate particulate matter from these types of aircraft engines. A sensitivity analysis was undertaken to estimate emissions for turboprop, turboshaft and piston-engine aircraft. In addition, as part of the sensitivity analysis (refer to Chapters 5 and 6 and Appendices D and E), the Calvert methodology (John, 2006) was reviewed and some changes made to the assumption used in EDMS with regard to reported smoke number “zeros” to allow estimates of particulate matter to be made for jet aircraft not calculated by EDMS.

Alternative Aircraft Fuels

The majority of aviation fuel consumed in the U.S. is jet fuel as opposed to AvGas (U.S. Energy Information Administration, 2011). Consequently, the primary focus of aircraft alternative fuels is on alternatives to jet fuel. Such fuels are being derived from natural gas, coal, oil sands, and biomass sources. Viable biomass alternative fuels are not ethanol-based, but use biomass feedstocks with advanced chemical processing to produce fuel. Newer alternative fuels are frequently referred to by their source feedstock (coal, natural gas, or a specific plant or animal biomass) and their chemical processing methods, such as Fischer-Tropsch (FT) or hydroprocessed renewable jet (HRJ).

Commercial airlines have tested alternative fuels blended with Jet A-1 on a limited number of overseas flights (RAND, 2009). The U.S. Air Force has a 2016 goal of “acquiring half of the service’s annual domestic aviation fuel requirement via alternative blends derived from locally sourced feedstocks” (Grace, 2011). It is certifying the use of alternative fuels for unrestricted operations in aircraft, typically flying using a 50/50 blend of JP-8 and synthetic fuel. The U.S. Air Force has flown aircraft with a blend of biomass-derived and conventional JP-8 fuel. Through the Commercial Aviation Alternative Fuels Initiative (CAAFI), the FAA, airlines, aircraft and engine manufacturers, energy producers, researchers, and other U.S. Government agencies are working to encourage the development of alternative aviation fuels and ASTM International standards for alternative fuels. ASTM International has approved alternative jet fuel specification in annexes to ASTM D7566 (ASTM, 2011) for FT and HRJ fuels blended with at least 50% conventional jet fuel. The U.S. Air Force is in the process of certifying military aircraft to use FT and HRJ fuels. U.S. Air Force aircraft and commercial aircraft have successfully flown with 50/50 blends, by volume, of FT/JP-8 and HRJ/JP-8. As such, those two types of fuels have a high technology readiness level. As alternative fuels are developed, certified, and become more available and affordable, demand will increase and result in growing potential environmental benefits.

Large reductions in particulate matter emissions are possible with these newer, alternative fuels. Typically, the FT and HRJ fuels are naturally low in sulfur and aromatics. The reduced sulfur content dramatically reduces the emissions of oxides of sulfur (SO_x), a source of secondary particulate matter emissions. RAND (2009) estimates that particulate matter and secondary particulate matter may be reduced by more than 10% when compared with Jet-A, and that one plant-based (camelina) HRJ fuel may reduce carbon dioxide (CO_2) emissions by over 80% during the life-cycle from field to wake. The Alternative Aviation Fuel Experiment (AAFEX) (Anderson et al., 2011, Beyersdorf and Anderson, 2009, Bulzan et al., 2010) found that engine carbon monoxide (CO), total hydrocarbon (THC), and NO_x and particulate matter emissions are reduced for alternative fuels derived from coal and natural gas when compared with emissions from JP-8. U.S. Air Force emission tests (Corporan and Cheng, 2010 and Corporan et al., 2007) on turboshaft engines also show $PM_{2.5}$ emissions are reduced for alternative fuels derived from natural gas when compared with emissions from JP-8. The FAA’s Center of Excellence PARTNER Project 17 (Hileman et al., (2009) (complete) and Project 20 (Missouri University of Science and Technology, 2011a) are working with the aviation community to gather and report accurate emissions data for several alternative fuels. NASA”s Alternative Aviation Fuel Experiment II (AAFEX II) project tested HRJ biofuel on a NASA DC-8, parked at

Palmdale, California, to measure its performance and emissions (Finneran, 2011). Analyses of data from AAFEX II experiments and the AAFEX II report were not available during the ACRP 02-23 project. Table 9 in Appendix A summarizes key $PM_{2.5}$ emission data for jet-fueled aircraft.

GROUND SUPPORT EQUIPMENT EMISSIONS

Ground support equipment (GSE) is a term used to describe the vehicles that service aircraft after arrival and before departure at an airport. The types of GSE at airports includes aircraft tugs, baggage tugs, belt loaders, fuel trucks, catering trucks, cargo trailers, water trucks, lavatory trucks, cabin service, and cargo loaders. The term can also refer to buses used airside to transport passengers between remote aircraft and terminals. Landside road vehicles are dealt with separately under the road vehicle category, although many parallels with GSE exist.

The calculation of GSE emissions, engine emission standards, alternative fuels and their impact on $PM_{2.5}$ for nonroad equipment were reviewed in the U.S. and Europe. It was found that there is no simple way to segregate volatile and non-volatile emissions (primary and secondary). Therefore, only total particulate matter emissions are presented for GSE in the ACRP 02-23 project.

GSE Alternative Fuels

EDMS already contains emission factors for alternative fuels used by GSE including LPG, CNG, and electric GSE. Electric GSE offers the greatest reductions of directly emitted particulate matter compared with other alternative fuels (U.S. FAA, 2010a), but can only be implemented where vehicle replacement is an option and only for certain applications. Viable electric GSE includes baggage tugs and belt loaders. Other specialist airside electric vehicles are being tested. Electric aircraft push-back tugs tend not be very flexible and are unable to deal with larger aircraft because of their relatively modest capacity.

Other alternative fuels include low-sulfur diesel, ethanol, methanol and biodiesel blends. The NONROAD emission factor model equations can be used to calculate low-sulfur diesel (EDMS uses NONROAD emission factors, but assumes a pre-set sulfur content). Specific emission factors for ethanol, methanol, and biodiesel blends are more difficult to estimate, although Table 3 under “Road Vehicle Alternative Fuels” gives some broad factors that can be used to convert particulate matter emissions from gasoline to bioethanol or diesel to biodiesel.

ROAD VEHICLE EMISSIONS

The calculations for road vehicle emissions, engine emission standards, alternative fuels and the impact of alternative fuels on $PM_{2.5}$ emissions were reviewed for road vehicles in the U.S. and Europe. EDMS uses the MOBILE6.2 model to calculate road vehicle emissions. It should be noted that while EDMS continues to use MOBILE, the MOBILE model has now been replaced outside EDMS by the newer MOVES model (U.S. EPA, 2010c). In theory, it would be better to use the updated MOVES model for the calculation of road vehicle-related emissions. However, for consistency with EDMS, the ACRP 02-23 project primarily uses MOBILE6.2 (U.S. EPA, 2003a, 2003b).

MOBILE6.2 assumes that total exhaust particulate matter is made up of three factors for recent years—organic derived particulate matter, elemental particulate matter, and sulfur-derived particulate matter. For gasoline, the first two factors are combined in MOBILE due to a lack of separate data. For diesel, all three factors are separate. MOBILE also calculates particulate matter from brake and tire wear.

Road Vehicle Alternative Fuels

Road vehicle alternative fuels are similar to those for GSE and include low-sulfur diesel, natural gas, electric, E85 (petrol/ethanol blend), M85 (petrol/methanol blend), B85 (diesel/biodiesel blend), and B100. MOBILE6.2 can be used to calculate low-sulfur and natural gas emission factors.

As part of the literature review, a comparison was made between key literature sources and the change in particulate emissions of biodiesel blends in vehicles, as summarized in Figure 6. Table 3 summarizes adjustments factors for road vehicles from a literature review undertaken by AEA (2008).

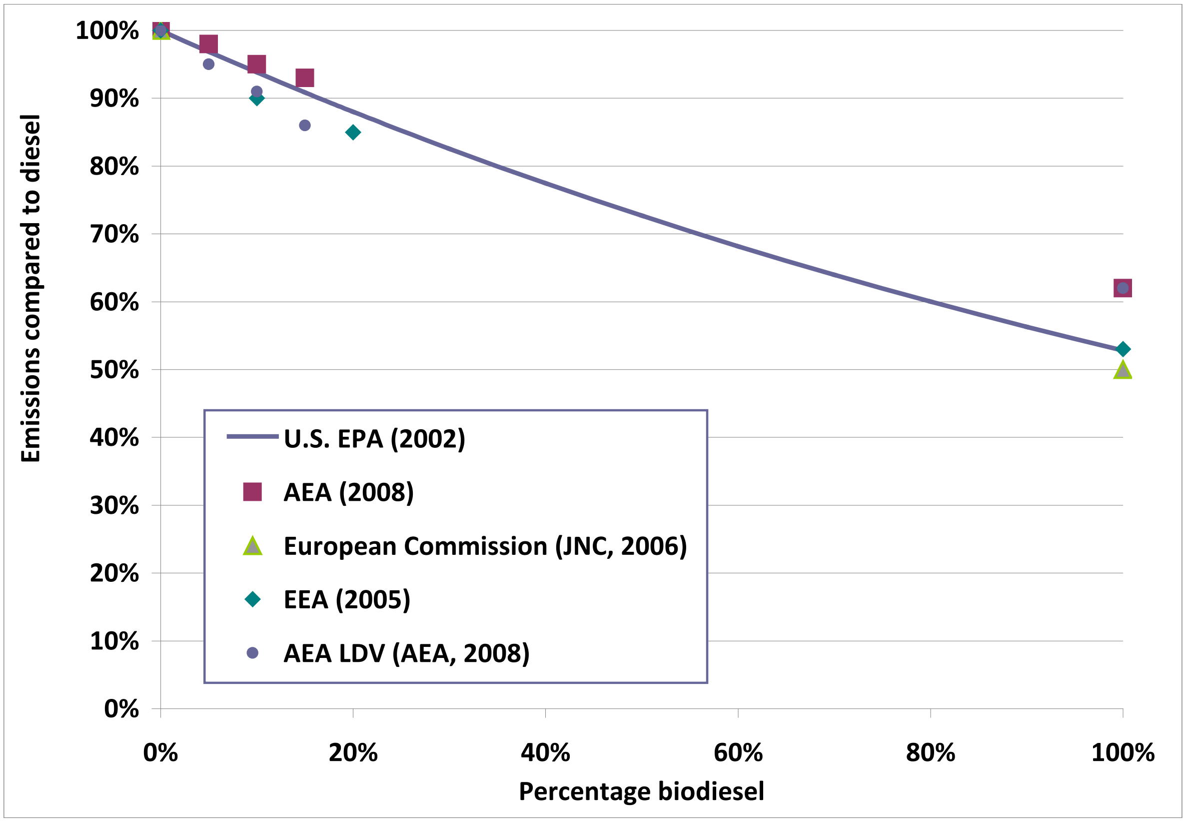


Figure 6 – Effect of Biodiesel Blends on Emissions of Particulate Matter from Road Vehicles

Table 3 – Adjustment Factors for Particulate Matter Emissions from Alternative Fuels

Vehicle	Fuel	Blend	Factor	Relative to
All	Bioethanol	E5	0.80	Gasoline
		E10	0.60	
		E15	0.40	
		E85	0.80	
Light Duty Vehicle (LDV)	Biodiesel	B5	0.95	Diesel
		B10	0.91	
		B15	0.86	
		B100	0.62	
Heavy-Duty Vehicle (HDV)	Biodiesel	B5	0.98	Diesel
		B10	0.95	
		B15	0.93	
		B100	0.62	
HDV	Biogas	100%	0.30	Diesel

Source: AEA, 2008

OTHER EMISSIONS

The term “other emissions” refers to emissions from on-airport sources other than the major sources discussed above (aircraft, APU, GSE, and road vehicles) and are generally much lower. This category includes emissions from:

- Stationary sources such as heating plant
- Training fires
- Construction activities
- Aircraft maintenance activities
- Fugitive emissions from fuel handling (aircraft and vehicular)

Of these sources, stationary sources and training fires typically have the highest particulate matter emissions and were the principal focus for the calculations of “other emissions” performed in the ACRP 02-23 project. Construction emissions can also be a sizeable source of particulate matter, but are limited to the period of construction and were, therefore, not addressed in the ACRP 02-23 project. Likewise, aircraft maintenance emissions and fugitive emissions from fuel handling are typically minor compared with other sources and were not addressed.

As discussed in the results in Chapter 6 and Appendix E, emissions from stationary sources and training fires were generally found to contribute only low levels of $PM_{2.5}$ relative to the major sources. In addition, the potential impact of alternative fuels from other sources (as listed above) was considered to be small. Consequently, alternative fuels for these sources were not considered further in the ACRP 02-23 project.

DISPERSION MODELING AT AIRPORTS

The purpose of dispersion modeling is to convert the emissions inventory results to ambient (i.e., outdoor) concentrations at key locations (i.e., receptors) such as located at airport public access points, along the airport perimeter and in the airport vicinity. Dispersion models are used to calculate the movement of the emissions due to meteorological conditions (e.g., wind speed and direction) and the resultant ambient concentrations at receptors. The FAA (2006a) *Order 1050.1E Change 1: Environmental Impacts: Policies and Procedures* identify the methods and models that are required when conducting air quality evaluations under the National Environmental Policy Act. Dispersion modeling for the evaluation of airport air quality impacts must be prepared using EDMS. EDMS invokes EPA’s AERMOD dispersion model to translate the emissions inventories it calculates into predicted concentrations of air pollutants. AERMOD/EDMS incorporates information on the spatial arrangement and emissions characteristics of airport sources, terrain and elevation, meteorological variables, and other physical considerations when predicting concentrations. 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 modeled results (i.e., by terminal area/concourse, aircraft mode, and internal and external roadways) and AERMOD (Version 09292) run outside of EDMS. However, it should be noted that AERMOD is a short-range dispersion model used to assess local air quality impacts; it does not include chemical interactions that result in the formation of secondary atmospheric particulate matter. When using EDMS/AERMOD, secondary particulate matter can only be accounted for by adding a background particulate matter component. Therefore, an estimate of total background particulate matter has been added in the ACRP 02-23 project with no separation of primary and secondary atmospheric particulate matter.

CHAPTER 3:

CASE STUDY AIRPORTS

The purpose of this chapter is to summarize the methodology used to identify the case study airports for which the local air quality impacts of airport-related $PM_{2.5}$ have been quantified in Chapter 6 and Appendix E.

EVALUATION AND SELECTION PROCESS

Selected from a pool of the FAA's 388 primary airports, 138 candidate airports were subjected to further evaluation based on their activity levels. The evaluation criteria used in identifying, evaluating and selecting the case study airports were initially identified in the original ACRP 02-23 project proposal. The final evaluation criteria, case study airport justification and recommended airport selection were presented to the ACRP 02-23 project panel and agreed upon. Importantly, the principal evaluation criteria were the availability and appropriateness of data for those airports that were most likely to participate in the ACRP 02-23 project.

Factors that affect $PM_{2.5}$ formation, dispersion, and reduction at airports were also considered to be important. These include fuel types (e.g., jet fuel, AvGas, biodiesel), emission sources and performance characteristics (e.g., aircraft, GSE, road vehicles), particulate matter size and composition (PM_{10}, $PM_{2.5}$ and $PM_{0.1}$), climatological and meteorological conditions (e.g., temperature, humidity, wind speed), and various spatial (distances from source to receptor) and temporal (travel and residence times) factors. The techniques by which airport-related $PM_{2.5}$ emissions and the effects of alternative fuels are assessed (e.g., emission factors, dispersion models, air quality monitoring methods) are similarly viewed as important. Therefore, the following evaluation criteria (listed in alphabetical order) were considered:

- Activity levels conducive to conducting a $PM_{2.5}$ assessment
- NAAQS attainment status for $PM_{2.5}$
- Existing emissions inventory, atmospheric dispersion, air quality monitoring, and airport activity data
- Existing or planned alternative fuels programs
- Meteorology, climate, geography and demographics
- Willingness to participate in the ACRP 02-23 project

Based on the screening process, discussed further in Appendix B, a total of 16 airports were viewed as good representatives of the criteria considered necessary to assess the effects of alternative fuels on $PM_{2.5}$ emissions and concentrations.

SELECTED CASE STUDY AIRPORTS

From the 16 potential case study airports identified in the screening process, the following five airports were identified as being the best representatives of all of the candidate airports considered based on data availability, willingness to participate, $PM_{2.5}$ non-attainment designations, alternative fuel programs and the other evaluation criteria.

- **Hartsfield-Jackson Atlanta International Airport (ATL) –** ATL is the busiest airport in the U.S. and is located in a mid-latitude warm climate. Emissions inventories have been conducted recently at this airport, although up-to-date atmospheric dispersion modeling is absent. The City of Atlanta (the airport operator) and its airline tenants are planning alternative fuel programs.

- **Las Vegas McCarran International Airport (LAS) –** Although the area surrounding LAS currently attains all $PM_{2.5}$ NAAQS, it is located within a "serious" PM_{10} non-attainment area. It represents a large-hub, commercial service airport (ranked seventh in the U.S.) in a mid-latitude, warm and arid climate. A $PM_{2.5}$ air monitoring network exists in the area, and a recently prepared airport emissions inventory and dispersion modeling analysis of $PM_{2.5}$ is available. Moreover, this assessment was conducted using the Total Airspace and Airport Modeler (TAAM) airfield simulation. Extensive GSE survey data on an airline-by-airline basis were available, as were operating time data, and detailed traffic and stationary source data.
- **Manchester-Boston Regional Airport (MHT) –** MHT is representative of a small-hub, commercial service airport (ranked 66th in the U.S., evenly mixed between commercial, air taxi, and General Aviation (GA)). It is located in a mid-latitude, cold-weather climate. An airport emissions inventory was recently completed for MHT, but dispersion modeling is absent.
- **Philadelphia International Airport (PHL) –** PHL represents a large-hub, commercial service airport (ranked 18th in the U.S., evenly mixed between commercial, commuter, and air taxi). It is located in a mid-latitude temperate climate on the east coast. The airport is in a non-attainment area for the annual and 24-hour $PM_{2.5}$ NAAQS, and has an existing and expanding alternative fuel program. As part of the 2010 PHL Capacity Enhancement Program environmental impact statement (EIS), extensive emissions inventory and dispersion modeling data exist for this airport. The assessment was conducted with the use of TAAM airfield simulation, extensive GSE survey data, operating time data, and detailed traffic and stationary source data.
- **San Diego International Airport (SAN) –** SAN represents a large-hub, commercial service airport (ranked 26th in the U.S.). It is located in a mid-latitude, warm, west-coast climate. Emissions inventory and dispersion modeling analyses were prepared for SAN as part of the 2009 Master Plan Airport Improvement Program and 2010 Air Quality Management Plan. The assessments were conducted using the Airport and Airspace Simulation Model (SIMMOD) airfield simulation and included GSE survey data, operating time data, and detailed traffic and stationary source data.

Appendix B presents detailed information on the evaluation process, documentation of the representativeness of the case study airports to the overall U.S. airport system and documentation of other airports that were considered to be case studies.

CHAPTER 4:

CASE STUDY ALTERNATIVE FUELS

This chapter discusses the methodology used to select the alternative fuels for the scenarios discussed in Chapters 5 and 6 and in Appendices D and E.

The alternative fuels were selected using a multi-criterion screening process, heavily weighted toward the fuel's potential to reduce $PM_{2.5}$ emissions from the major contributors identified in the base case results in Chapter 6 and Appendix E. These major contributors were identified as:

- Aircraft (main engines, excluding piston-engine aircraft)
- APUs
- GSE and other specialized vehicles
- Road vehicles

The alternative fuels are representative of various chemistries (e.g., low-sulfur, low-aromatic feedstocks) and the ACRP 02-23 project considered the suitability for use, the likelihood of short-term (i.e., fewer than 10 years) commercial availability and the potential for life-cycle environmental improvement. For aircraft engines, the fuels have been limited to fuels which can be used in existing engines (i.e., drop-in fuels). Appendix C also discusses other potential challenges in implementing alternative fuels that have been taken into consideration.

EVALUATION AND SELECTION PROCESS

Summary of Methodology

The U.S. Department of Energy (DOE) (1992) defines the following alternative fuels for vehicles (i.e., road and off-road such as GSE) under the Energy Policy Act (1992):

- Biodiesel
- Electricity
- Ethanol
- Hydrogen
- Methanol
- Natural gas
- Propane

Several emerging fuels are under development and are also regarded by DOE as alternative fuels. These include biobutanol, biogas, biomass-to-liquids (BTL), coal-to-liquids (CTL), FT diesel, gas-to-liquid (GTL), hydrogenation derived renewable diesel, P-Series, and ultra-low-sulfur diesel.

The scope of the ACRP 02-23 project, as stated above, was limited to fuels with short-term commercial availability. In addition, the calculations of emissions are dependent on suitable emission data being available for the alternative fuel. These data also tend to be limited to those fuels that are available now, albeit in low volumes, rather than emerging fuels. Therefore, 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 in theory 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. At present, 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) have 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.

As discussed in Chapter 2 and Appendix A, a number of fuels for the main contributors were identified for further consideration.

Aircraft Main Engine and APU:

- Low-sulfur (or near-zero sulfur) Jet-A equivalent aviation fuel for aircraft main engines and APUs
- FT synthetic fuels (50/50 blends) derived from coal, natural gas or biomass and blended with Jet-A for use in aircraft main engines and APUs
- HRJ fuels (50/50 blends) derived from biomass and blended with Jet-A for use in aircraft main engines and APUs
- Grade 91/96UL AvGas for piston-engine aircraft

APU:

- Fixed electrical ground power (at gates) to replace some APU use (some APU use will always be necessary, e.g., for main engine starts)

GSE:

- Electrically powered vehicles
- LPG and CNG
- Low-sulfur diesel
- Ethanol blends E5, E10, E15, and E85
- Biodiesel blends B5, B10, B15, B20, and B100

Road Vehicles:

- Electrically powered vehicles
- Ethanol blends E5, E10, E15, and E85
- Biodiesel blends B5, B10, B15, B20, and B100
- Natural gas for road vehicles

The criteria used for assessing which of the above alternative fuels and source combinations should be included are outlined in Table 4, followed by a description of the screening process and the results. A more detailed discussion of each criterion is presented in Appendix C.

Each combination of alternative fuel and emission source was assessed in terms of each criterion's rating (e.g., High (H), Medium (M), Equivalent (E), Low (L), Yes (Y) or No (N)). For example, FT jet fuels, compared with JP-8 conventional fuel, have particulate matter emission reductions that fall in the range 25% to 75% and, therefore, "Change in $PM_{2.5}$ Emissions" for this fuel and source combination has been classed as "M." Most of the criteria determinations were based on expert knowledge and professional judgment, with the exception of "Change in $PM_{2.5}$ Emissions" and "Cost of fuel relative to conventional." "Change in $PM_{2.5}$ Emissions" data are based on the literature review (Chapter 2 and Appendix A) and specific sources are cited in the text in this Chapter. "Cost of fuel relative to conventional" is primarily based on the U.S. DOE fuel prices report (U.S. DOE, 2011).

Table 4 – Alternative Fuels Matrix – Criteria and Definitions

Criterion	Definition	Rating
Change in $PM_{2.5}$ emissions (H, M, L)	The relative decrease in emissions compared with the dominant existing fuel/engine (or vehicle).	H = More than 75% reduction M = Between 25% and 75% reduction L = Less than 25% reduction
Availability of fuel (H, M, L)	Is the fuel currently available?	H = Widespread availability of fuel/blend in many states, though some regional variability M = Frequently available, but not at all sites/locations and would often require additional infrastructure (e.g., tanks) L = Limited/not readily available
Availability of new vehicles (H, M, L)	Are vehicles that can use this fuel currently available or are they likely to be available in the short-term? It should be noted that model availability depends on purpose.	H = Many model types readily available for this fuel type and many being used M = Many model types available that can use this fuel, though not universal L = Not many models available (if any) that can use this fuel
Cost to convert existing vehicles (H,M,L)	How much is it likely to cost to convert a typical vehicle?	H = More than $20,000 M = Between $200 and $20,000 L = Less than $200 N/A = no cost associated (i.e., for drop-in fuels)
Drop-in fuel for existing vehicle? (Y/N)	Can the fuel be used in existing vehicles with no modification?	Y/N or N/A
GHG life-cycle emissions (H, M, L)	GHG emissions of the alternative fuel relative to the primary conventional fuel. This figure includes the fuel processing (i.e., "well to wheel") emissions.	H = More than 90% of conventional fuel M = Between 40% and 90% of conventional fuel L = Less than 40% of conventional fuel
Emission data source reliability (H, M, L)	Is the source of the proposed emission factors based on reliable data?	H = Widely tested, many high-quality (government or referred journal) published studies with similar results for a range of vehicles M = Published studies, but limited to one or two vehicles L = No specific data, assumptions based on similar source (e.g., road vehicle for GSE) or based on calculations
Cost of fuel compared with conventional (H, E, L)	This is the marginal increase in fuel cost compared with the dominant existing fuel.	H = More than 125% of conventional fuel E = Equivalent price to conventional fuel – between 75% to 125% of conventional fuel L = Less than 75% of conventional fuel (N/A where no data on cost are available. Variable and N/A assume worst case, high cost)

Criterion	Definition	Rating
Cost of vehicles compared with conventional (H, M, L)	This is the marginal increase in vehicle cost compared with the dominant existing vehicle type.	H = More than 200% M = Between 110% and 200% L = Less than 110% N/A = no additional cost (i.e., for drop-in fuels)
Additional infrastructure needed (H, M, L)	What additional infrastructure is needed for the fuel to be used?	H = Additional equipment such as compressors, high pressure buffers and tanks needed M = Additional tanks, similar to those already in existence, would be needed (e.g., for different blends) L = Assumes that diesel, electricity and gasoline are readily available on, or near, the site N/A = no additional cost associated
Warranty validity issue (Y/N)	Could the use of this fuel result in vehicle/engine warranty being invalidated?	Y/N

Note that “vehicle” is used here to refer to aircraft, APU, GSE and road vehicles

Table 11 in Appendix C presents the results of the assessment of each fuel and source combination based on the ratings shown in Table 4 above. The H/M/L ratings were then converted into numerical scores between 0 and 3, where 3 related to the best ranking and 0 to the worst. For example, for “Change in $PM_{2.5}$ Emissions”, where a high decrease in emissions is desirable, H was awarded a score of 3, M = 2, L = 1, and N/A = 0. Conversely, for “Cost to convert existing vehicles”, H was awarded a score of 0, M = 1, L = 2 and N/A = 3 because a high cost is less desirable than no cost. The primary aim of this ACRP 02-23 project was to assess potential reductions in $PM_{2.5}$, in terms of emissions and impact. The use of the different criteria, in the context of this project, was to determine which fuel and source combinations to assess further, in terms of $PM_{2.5}$ emission and impact reductions at the case study airports. Therefore, these scores were summed based on a weighted total score, where 45% of the total was allocated to “Change in $PM_{2.5}$ Emissions” and the rest evenly distributed among the other criteria (i.e., 5% per criterion), with the exception of “Emission Data Source Reliability”, which was allocated 10%. The total scores were then converted to a percentage by dividing by 300. The consequence of this methodology was a significant bias towards those fuels where the $PM_{2.5}$ emission reduction is likely to be significant compared with the primary conventional fuel. For example, source and fuel combinations resulting in $PM_{2.5}$ reductions of more than 75% automatically had a total 45% scoring before any other criteria were considered. Those fuel and sources where either the final weighted result was less than 50% or the “Change in $PM_{2.5}$ Emissions” criteria was assessed as low or not applicable (i.e., a score of 1 or 0), were then discarded. This resulted in a list of the initial fuel and source combinations as shown in Table 5.

When a particular airport is assessing whether a particular alternative fuel should be taken forward, they should not necessarily use the weightings used in the ACRP 02-23 project. Instead, they should consider their own business priorities to determine the most appropriate weightings for their own context. The “pre-weighted” information is provided for airports’ use in Appendix C, and separately in the Guidance Document.

Table 5 – Initial Fuel and Source Combinations

Fuel and source
FT (natural gas) aircraft
FT (coal) aircraft
91/96UL AvGas for piston-engine aircraft
FT (natural gas) APU
FT (coal) APU
Electricity to replace some APU use
Electric GSE, where available
LPG GSE replacing diesel GSE, where available
CNG GSE replacing gasoline GSE, where available
CNG GSE replacing diesel GSE, where available
E10 in gasoline-fueled GSE
B100 in diesel-fueled GSE
Natural gas road vehicles to replace diesel
Electric road vehicles
E10 in gasoline-fueled road vehicles
E15 in gasoline-fueled road vehicles
B100 in diesel-fueled road vehicles

SELECTED CASE STUDY ALTERNATIVE FUELS

As E10 and E15 are likely to produce similar reductions in $PM_{2.5}$ emissions, it was decided to include only one of these fuels. E15 was removed from consideration as it is more costly to convert GSE and road vehicles to run on this type of fuel, and the data are not as reliable.

As B100 is the only biodiesel blend included in Table 5, B20 was included in the list of fuels for analysis, even though the potential change in $PM_{2.5}$ emissions was low compared with conventional diesel. There is a greater availability of vehicles that can use B20 compared with those that can use B100.

Table 6 lists the final alternative fuels and sources referred to in Chapters 5 and 6.

Table 6 – Final Fuel and Source Combinations

Fuel and Source
FT (natural gas) aircraft
FT (coal) aircraft
91/96UL AvGas for piston-engine aircraft
FT (natural gas) APU
FT (coal) APU
Electricity to replace some APU use
Electric GSE, where available
LPG GSE replacing diesel GSE, where available
CNG GSE replacing gasoline GSE, where available
CNG GSE replacing diesel GSE, where available
E10 in gasoline-fueled GSE
B20 in diesel-fueled GSE
B100 in diesel-fueled GSE
Natural gas road vehicles to replace diesel
Electric road vehicles
E10 in gasoline-fueled road vehicles
B20 in diesel-fueled road vehicles
B100 in diesel-fueled road vehicles

The following points should be noted:

- The fuels listed in Table 6 may only apply to sources that have a small impact on total particulate matter emissions at a particular airport and, therefore, the relative change in total emissions and air quality impact will be minimal.
- HRJ fuels for aircraft were not included due to a lack of relevant emission data. However, as noted in Appendix C, since FT and HRJ fuels have similar structures, it is likely that the relative changes in emissions will be of a similar order of magnitude for aircraft.
- There is uncertainty with regard to the emission factors for natural gas for road vehicles, which could result in higher emissions than would be expected. Again, this is discussed further in Appendix C.

CHAPTER 5:
METHODOLOGY

This chapter 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, for the base case and the alternative fuel scenarios. Further details of the methodology are contained in Appendix D. The principal components of the methodology comprise emissions inventories, atmospheric dispersion modeling, and air quality monitoring data.

- **Emissions Inventories** – The purpose of an emissions inventory is to quantify the amounts (i.e., total mass) of air emissions by emission source. The emissions in the ACRP 02-23 project are reported in kilograms or tons. The emissions inventories were separated for the base case by aircraft operating mode, aircraft type, non-volatile versus volatile emissions, GSE type and fuel, and other sources, as a means of comparing case study airports and evaluating alternative fuels. The sources of emissions included in the inventories are identified as aircraft, GSE, APUs, on/off-airport road vehicle operations and airport-related stationary sources (e.g., boilers, generators).
- **Atmospheric Dispersion Modeling** – The purpose of the atmospheric dispersion analysis is to convert the emissions inventory results to ambient (i.e., outdoor) concentrations of $PM_{2.5}$ at locations (i.e., receptors) located at airport public access points, along the airport perimeter and in the airport vicinity. Dispersion models are used to calculate the movement of the emissions due to meteorological conditions (e.g., wind speed and direction) and the resultant ambient concentrations at receptors. The estimated concentrations in the ACRP 02-23 project are reported in micrograms per cubic meter of air ($\mu g/m^3$).
- **Ambient Monitoring Data** – The purpose of the ambient monitoring data is to determine background concentrations, to account for the contributions from non-airport regional and natural sources of $PM_{2.5}$. The background concentrations are added to the atmospheric dispersion modeling results to obtain a total air pollution concentration.

The following list contains the key reference documents on which the base case analyses were based, followed by the analysis year used. Further details are outlined in Table 12 in Appendix D and in the following sections.

- Hartsfield-Jackson Atlanta International Airport 2008 Air Emissions Inventory (ATL, 2010) – analysis year 2008
- Southern Nevada Supplemental Airport Environmental Impact Statement Air Quality Technical Report (LAS, 2010) – analysis year September 2007 to August 2008, plus updated 2009 stationary source data (LAS, 2011)
- Manchester-Boston Regional Airport 2007 Air Emissions Inventory (MHT, 2009) – analysis year 2007
- Philadelphia International Airport Capacity Enhancement Program Air Quality Technical Report (PHL, 2010) – analysis year 2004
- San Diego International Airport Air Quality Management Plan Baseline Emissions Inventory (SAN, 2009) – analysis year 2008

EMISSIONS INVENTORY FOR BASE CASE

Where available, airport-specific data were used to develop the emissions inventory and dispersion modeling analyses for the base case. Data included 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.

Within each analysis year and for each airport, all the data elements were kept consistent. For example, the analysis year for ATL 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.

EDMS is the FAA required model for assessing airport-related air quality impacts. Therefore, to estimate airport-related emissions, the data discussed above were used with FAA's EDMS (Version 5.1.2) (U.S. FAA, 2009) 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. Appendix D discusses the general EDMS and AERMOD control options, APU operating time, choice of geographic locations for calculating the impact (i.e., receptors), terrain data used, meteorological data used, mixing height, and monitoring data used.

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) (U.S. EPA 2003b) and the California Air Resources Board (CARB) (2006a) Motor Vehicle Emission Factor Model (EMFAC2007) model (used for SAN) 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 refers to vehicles that access the public roadways within the on-airport road network and external road network. Therefore, this includes some airport-related rolling stock. The boundary for road vehicles was dependent on the extent that the data were available. In most cases, the original data used had been compiled for analysis in compliance with 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). To enable cross comparison between different airports, road vehicle emissions are presented in Appendix E in grams per vehicle mile.

NONROAD (U.S. EPA, 2008) and OFFROAD2007 (CARB, 2006b) models were used for SAN 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.

Non-Volatile and Volatile $PM_{2.5}$ Emissions

The emissions inventories in the ACRP 02-23 project report $PM_{2.5}$ emissions as non-volatile and volatile, where information is available to allow that distinction (i.e., for aircraft main engines and road vehicles).

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 (ICAO 2007 and 2011). 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 (discussed further in Appendix D). 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

The justification for the alternative fuel and source combination scenarios are discussed in Chapter 4 and Appendix C. HRJ fuels have not been analyzed separately in the ACRP 02-23 project due to lack of data at the time of study (Whitefield et al., 2011) as well as the similarity of the chemical structure of HRJ fuels to FT fuels, which are included.

To calculate the alternative fuel emissions for each fuel and source combination, scaling factors were applied. These scaling factors were related to:

- The ratio of the scenario emissions to the base case emissions per source and fuel combination.
- The alternative source fuel penetration (i.e., whether a 100% of that source use the fuel).

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 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 are 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.

Ratio of Scenario Source Type Emissions to Base Case

The ratio of emissions of the alternative fuel versus the base fuel for each relevant source and fuel type were calculated. These ratios were used to scale the base case emissions to the alternative fuel scenario emissions, assuming all relevant sources use the alternative fuel as indicated in the equation below. The actual ratios used are shown in Table 13, Table 14, and Table 15 in Appendix D, though for some fuel and source combinations the alternative fuel emissions have been calculated using either EDMS databases (e.g., GSE) or MOBILE6.2 (e.g., for road vehicles) rather than using a specific ratio.

$$AFE = Base \times AF$$

Where:

AFE = Alternative fuel emissions
Base = Base case emissions for source and fuel type
AF = Alternative fuel ratio

Alternative Fuel Penetration

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). Therefore, a penetration factor, P (ranging from 0 to 1) was applied to scale the emissions for each alternative fuel and source type. The remainder (1–P) of the non-penetrated sources' emissions were assumed to be as per the base case calculations. For example, if only 2.6% of diesel-fueled road vehicles use B100, then the penetration factor (P) applied is 0.026 for the B100 road vehicle emission calculation, and 0.974 (1–P) for the base case road vehicle emission calculation:

$$Scenario = (AFE \times P) + ((1-P) \times Base)$$

Where:

Scenario = Scenario emissions per source and fuel type
Base = Base case emissions for source and fuel type
AFE = Alternative fuel emissions for source type
P = Penetration factor

For each of the source and fuel combinations, a number of penetration options have been considered. 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, and a penetration factor of 1 has been assigned. The 91/96UL AvGas fuel can, in theory, be used as a drop-in fuel in many piston-engine aircraft (and is the main fuel in many countries). 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 penetration factor of 1 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 has 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 (2011) fuel use projections in 2020) and expert knowledge. Other penetration factors for the different scenarios and the sources and assumptions made are outlined in Table 16 in Appendix D.

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 modeled 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 $\mu g/m^3$ and can be separated into individual source contributions of 2 $\mu g/m^3$ from aircraft engines, 4 $\mu g/m^3$ from Terminal A and 2 $\mu g/m^3$ from Terminal B (where terminal sources are related to GSE and APU), 1 $\mu g/m^3$ from roadways and 1 $\mu g/m^3$ 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 above, 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 $\mu g/m^3$ to 2 $\mu g/m^3$. If no other change in emissions is assumed, then the total concentration at the same receptor for this scenario is now 8 $\mu g/m^3$ (i.e., a reduction of 2 $\mu g/m^3$). Similarly, for each scenario, the relative change in emissions between the base case and the scenario (scenario/base) was applied to the relevant source contribution’s dispersion modeled results for each receptor point (i.e., individual locations) as indicated in Table 19 and Table 20 in Appendix D. 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 than the base case impact. However, for the ACRP 02-23 project it was assumed to be the same hour.

The piston-engine and turboprop aircraft scenarios (which include turboshafts) have emission results reported in Chapter 6 and Appendix E only as part of the sensitivity analysis. This is due to EDMS not incorporating the calculations of these two source types for $PM_{2.5}$.

SENSITIVITIES OF ANALYSIS

EDMS does not typically include $PM_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no FAA accepted emission factors for these aircraft. Therefore, a number of alternative methodologies were used in the ACRP 02-23 project to estimate emissions for those aircraft for which EDMS does not estimate $PM_{2.5}$ emissions. A sensitivity analysis on the impacts of these methodologies upon aircraft emissions was conducted and is reported in Chapter 6 and Appendix E. For those aircraft where there is no appropriate alternative methodology to calculate emissions, emissions were scaled based on the average emissions for that aircraft size. This methodology for determining $PM_{2.5}$ emission factors and the sensitivity analysis for aircraft engines not covered by EDMS was reviewed and discussed with the FAA as part of the ACRP 02-23 project. The methodology is described in detail in Appendix D.

Alternative Fuels

As part of the sensitivity analysis, the base case emissions from turboprop (including turboshaft) and piston-engine aircraft were scaled in line with the scaling ratios in Table 14 in Appendix D with an assumed 100% penetration. This enables those airports with a high proportion of turboprop, turboshaft, and piston-engine aircraft to access the potential change in emissions associated with the use of alternative fuels for those aircraft types.

CHAPTER 6:

RESULTS

This chapter presents and discusses the results of the base case and alternative fuel scenarios $PM_{2.5}$ emissions inventories and air quality impact analyses for the five case study airports. Emissions results for the base case are reported in kilograms rather than tons for consistency and comparison with smaller source specific values (although results are also shown in tons in Table 7 for information purposes). 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 98th percentile of the 24-hour average). The alternative fuel scenarios results are based on the relative change on a number of key indices representing the impact that each alternative fuel and source combination would have on $PM_{2.5}$ emissions and local $PM_{2.5}$ pollutant concentrations at each case study airport. Appendix E provides additional details related to the emissions inventories and air quality impact at the five case study airports for all scenarios.

BASE CASE

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 overall EDMS-generated results of the $PM_{2.5}$ emissions inventory for the five case study airports (in kilograms per year) are presented in Table 7 and Figure 7 by emission source category.

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 type and size of the aircraft, the airfield taxi and delay times, and meteorological conditions. For example, the larger airports tend to operate larger aircraft and experience greater ground-based taxi times than the smaller airports. GSE emissions are mostly a function of the types of equipment, fuel type used, engine size, age of equipment and operating time. $PM_{2.5}$ emissions tend to be higher for diesel-fueled GSE than those for gasoline-fueled equivalents.

APU emissions are a function of the number of aircraft that operate APUs and the duration of APU use. Thus, when comparing airports, it is important to note whether gate power and pre-conditioned air are present and how many gates are equipped, as such infrastructure services can substantially reduce APU operating times. The larger airports tend to have gate power and pre-conditioned air at the terminals, while smaller airports typically have fewer of these gate facilities, use diesel powered ground power units, or have more aircraft that do not use APUs.

Road vehicle emissions are a function of the traffic volumes, travel distances, and emission factors, which are dependent on regional emissions controls, vehicle speed and meteorological conditions. For this analysis, roadway emissions are split into two geographic distinctions—on-airport and off-airport. Off-airport roadways may, in some cases, include elements of local traffic not related to the airport.

Table 7 – Annual $PM_{2.5}$ Emissions Inventory by Source Category (kg unless specified)

Source Category	ATL	LAS	PHL	SAN	MHT
Aircraft	32,157	17,604	16,647	7,596	1,853
Ground support equipment	9,829	4,114	14,940 (a)	582	945
Auxiliary power units	12,617	3,800	3,802	2,730	425
Parking facilities	304	86	333	243	11
On-airport roadways	1,798	302	1,212	163	85
Stationary sources	448	5,459	392	588	66
Training fires	—	—	2,819	—	—
On-airport total	**57,154**	**31,366**	**40,145**	**11,903**	**3,385**
Off-airport roadways	21,766	3,073	12,221	2,026	41
Grand totals	**78,920**	**34,440**	**52,366**	**13,928**	**3,426**
Grand totals (tons)	**87**	**38**	**58**	**15**	**4**
Aircraft landing/takeoff cycles	489,100	304,386	237,238	109,947	45,836
Passengers (1,000s)	78,125	42,133	24,507	17,759	1,948
Taxi-out time (minutes)	20.7	16.7	21.8	13.6	13.6
Taxi-in time (minutes)	10.8	6.54	6.70	3.78	4.50

Source: ATL (2010), LAS (2010), LAS (2011), PHL (2010), SAN (2009), MHT (2009), Bureau of Transportation Statistics, and FAA Aviation System Performance Metrics Database.

A dash (–) indicates that no data were available for these sources

(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.

Using the data shown in Table 7, aircraft represent between 41% and 63% of the total on-airport-related $PM_{2.5}$ emissions, while GSE represents between 5% and 37%. APUs represent between 9% and 22%, and road vehicles represent between 1% and 5% of the on-airport total $PM_{2.5}$ emissions. Table 7 also provides information on the number of aircraft landing and takeoff (LTO) cycles, passengers, and average taxi times as a means of giving the emissions totals a perspective.

The emission results highlight the differences between unique airports. For instance, the original data collected from LAS for use in the ACRP 02-23 project included re-suspended dust from roadways, which was not the focus of study at any of the other airports. Therefore, the roadway emissions reported in the ACRP 02-23 project for LAS do not include re-suspended roadway dust to enable a fair comparison to be made. Apart from LAS, which has a number of on-airport boilers and cooling towers, and PHL, which includes a fire training facility, stationary sources comprise a small percentage of the total on-airport-related $PM_{2.5}$ emissions.

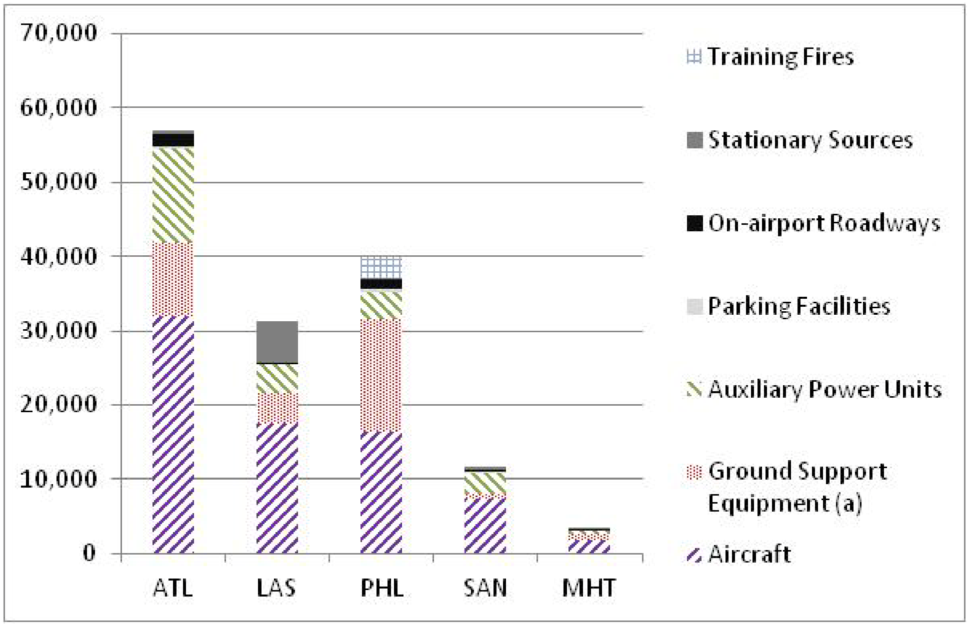


Figure 7 – On-Airport Annual $PM_{2.5}$ Emissions Inventory by Source Category (kg)

(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.

ALTERNATIVE FUEL SCENARIOS

The following section summarizes the alternative fuel scenarios for the EDMS-generated results for each isolated scenario, in terms of percentage reductions for the annual average and 24-hour 98th percentile, for the following key indices:

- The total on-airport emissions.
- The airport impact concentration at the location of the maximum airport impact concentration in the base case.
- The maximum distance from the airport to a threshold airport impact concentration level, termed the Radius of Influence (ROI). The ROI is defined as the distance that extends from the source (in this case, the airport reference point) to the farthest receptor distance at which the source has a concentration greater than a specific threshold for a given pollutant. The threshold level for the annual average is 0.3 $\mu g/m^3$ and for the 24-hour 98th percentile it is $1.2 \mu g/m^3$.
- The area in which the air quality impact from the airport is below the threshold level, referred to as the influence area. The threshold level for the annual average is 0.3 $\mu g/m^3$ and for the 24-hour 98th percentile it is $1.2 \mu g/m^3$.

Appendix E includes more detailed tabulated results for the annual average and the 24-hour 98th percentile.

The EDMS-generated results do not typically include results for piston-engine and turboprop aircraft. The emission results for these two generic aircraft types are discussed separately at the end of this chapter.

The percentage change was only calculated for on-airport roadways and parking lots due to lack of data availability to separate off-airport roadways (as discussed in Chapter 5). In addition, airport operators have some control over on-airport road vehicles but no control over off-airport road vehicle emissions. However, many of the vehicles traveling on on-airport roadways will also be traveling on off-airport roadways. Therefore, the percentage change would actually be larger than summarized below.

Summary Results

Figure 8 to Figure 14 provide the average and range of percentage reduction (alternative fuel scenarios relative to the base case) based on data from the five case study airports. Results at other airports would be expected to generally fall within these ranges, but may be smaller or larger depending on specific conditions (e.g., aircraft fleet mix, GSE fuel mix, level of operations) at the airport.

Emissions

In terms of the airport-related emissions, Figure 8 shows that the largest total on-airport emission reductions are provided by the following (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 warranty).
- Reducing APU use by providing electrical ground power and pre-conditioned air at 100% of gates.

The aircraft emission reductions occur throughout the LTO cycle, but the greatest reductions are during takeoff as that is the operating mode which creates the greatest emissions. The alternative fuel scenario results are dependent on the aircraft fleet mix (i.e., the proportion of jet-fueled aircraft) at each airport. The range of emission reductions for APU reduced use is dependent on the number of operations that have access to gate power and pre-conditioned air, the assumed APU operating times (which in the ACRP 02-23 project were up to 26 minutes), amount of gate delay, and the aircraft fleet mix (i.e., whether or not aircraft have an APU).

The emission reductions for the electric, LPG and CNG GSE scenarios are a function of the current fuel mix for the existing GSE and whether the existing types of GSE can be replaced with an alternative-fueled equivalent.

Of note, depending on the assumed base case emissions, replacing gasoline GSE with CNG equivalents may result in an increase in emissions. This result is primarily a function of the uncertainty of the emission factors used and does not necessarily mean that the emissions would actually increase.

Road vehicle alternative fuel scenarios provide a smaller reduction in overall airport emissions than those for drop-in aircraft and APU fuels, reducing APU use and some GSE alternative fuel scenarios.

Maximum Concentration

In terms of location of the maximum annual average and 24-hour 98th percentile airport impact concentrations, Figure 9 and Figure 10 show that the largest reductions are provided by the following (listed in descending order):

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

Given the nature of the aircraft emissions (i.e., spread out through the airport along taxiways and within the rest of the LTO cycle) and their proximity to the location of maximum concentration receptors (i.e., aircraft tend not to be a large contributor to maximum impact), the benefits of alternative fuel scenarios on reductions of the maximum concentration are not as great as the reductions in overall emissions for aircraft. The maximum concentrations are typically located where there is a large contribution from GSE and APU activities (i.e., near to gates); therefore, it is the GSE and APU scenarios that have the greatest reduction in maximum concentrations.

The concentration reductions for other scenarios are relatively small, with the exception of replacing all on-airport road vehicles with an electric equivalent, which is a hypothetical scenario and unlikely to be achieved.

It should be noted that the location of the largest maximum concentration is likely to change for a given alternative fuel scenario. Therefore, the Radius of Influence (ROI) and influence area results are better indications of the overall impact the different scenarios will have on local air quality.

Radius of Influence

The maximum distance from the airport to a threshold airport impact concentration level is referred to as the Radius of Influence (ROI). The threshold level for the annual average is 0.3 $\mu g/m^3$ and for the 24-hour 98th percentile it is $1.2 \mu g/m^3$.

Figure 11 shows that the largest reductions in the annual ROI are provided by the following (listed in descending order):

- 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 electric equivalents.
- Reducing APU use by providing electrical ground power and pre-conditioned air at 100% of gates.
- Replacing a 100% of GSE with available 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 warranty).

Figure 12 shows that the largest reductions in the 24-hour 98th percentile ROI are provided by the following (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.
- Replacing 100% of diesel with B100 in GSE (though it should be noted that this could have implications for GSE in terms of warranty).
- Reducing APU use by providing electrical ground power and pre-conditioned air at 100% of gates.

Similar to the maximum concentration, the reductions in ROI are not as great as the reduction in emissions. However, although GSE emissions contribute a large portion of the overall maximum concentration from all airport operations, they tend to influence a small area. Thus, GSE alternative fuel scenarios have a larger reduction for the maximum concentrations than for the associated ROI or influence area.

As with the maximum concentrations, road vehicle alternative fuel scenarios show a smaller reduction in the ROI than those for alternative fuel scenarios for aircraft and APUs and some GSE alternative fuel scenarios.

Influence Area

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 $\mu g/m^3$ and for the 24-hour 98th percentile it is $1.2 \mu g/m^3$.

Figure 13 and Figure 14 show that the largest reductions in both the annual average and the 24-hour 98th percentile influence area are provided by the following (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 maximum concentration and ROI are statistics that provide a limited focus spatially (e.g., at one receptor point for the maximum) and the influence area measures the overall impact taking into account the spatial variations in emissions. Therefore, results generally show a greater percentage reduction in influence area for aircraft-related scenarios than that for the maximum concentration and ROI due to the spatial spread of the aircraft emissions. As with the ROI, road vehicle alternative fuel scenarios show a smaller reduction of influence area than those for alternative fuel scenarios for aircraft and APUs and some GSE alternative fuel scenarios.

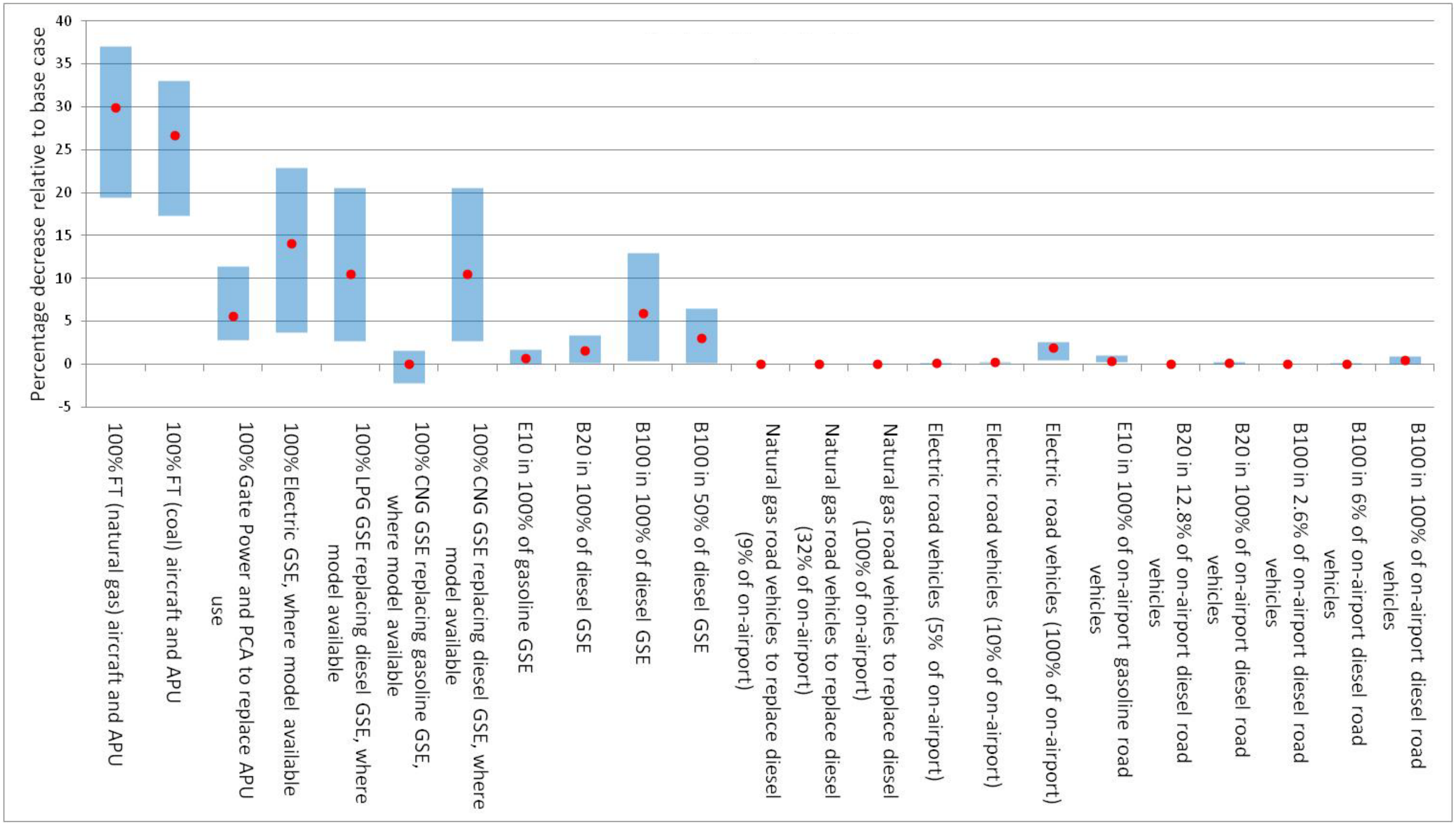


Figure 8 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Total Airport Emissions

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.

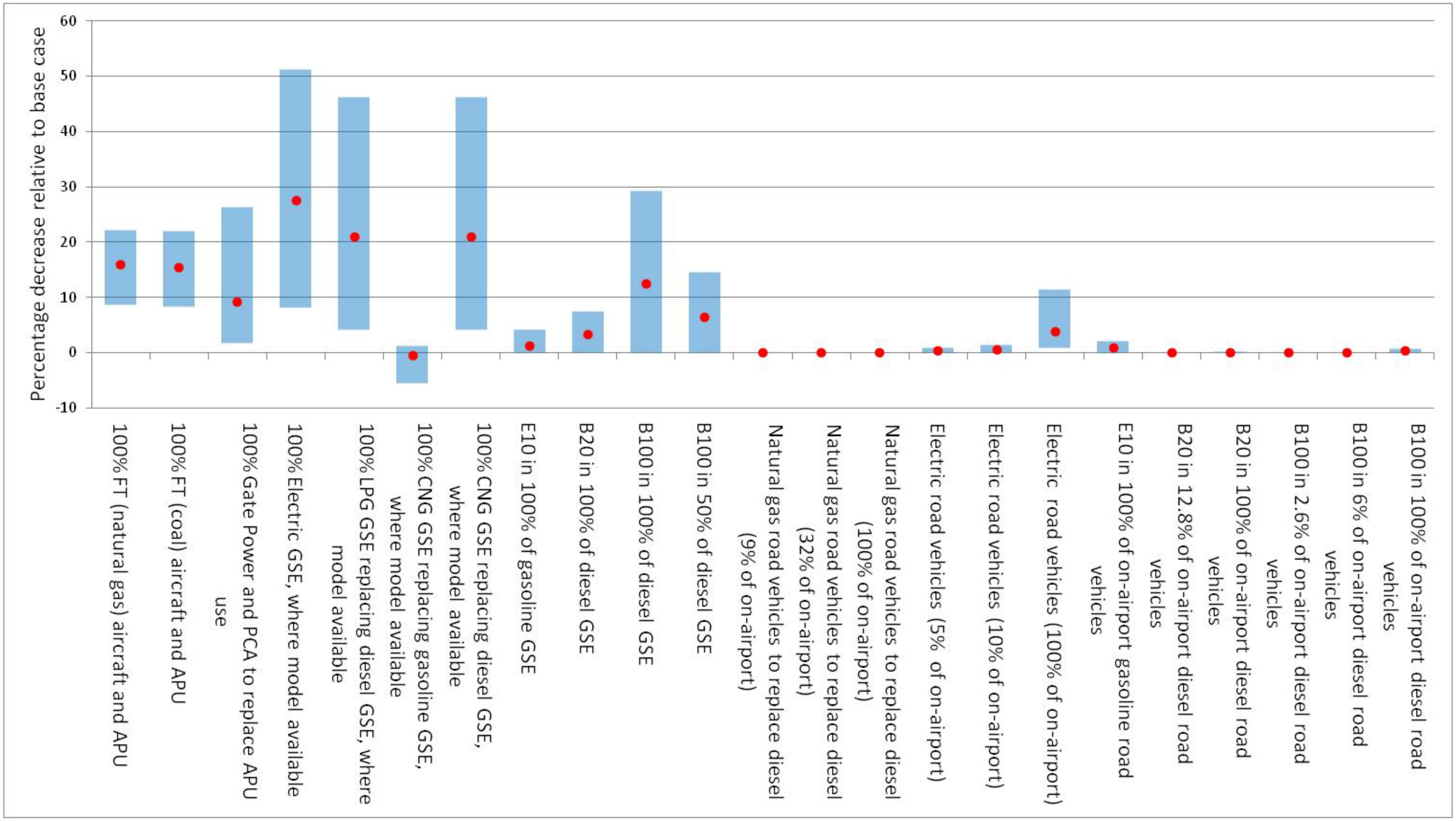


Figure 9 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Maximum Airport Annual Average Impact

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.

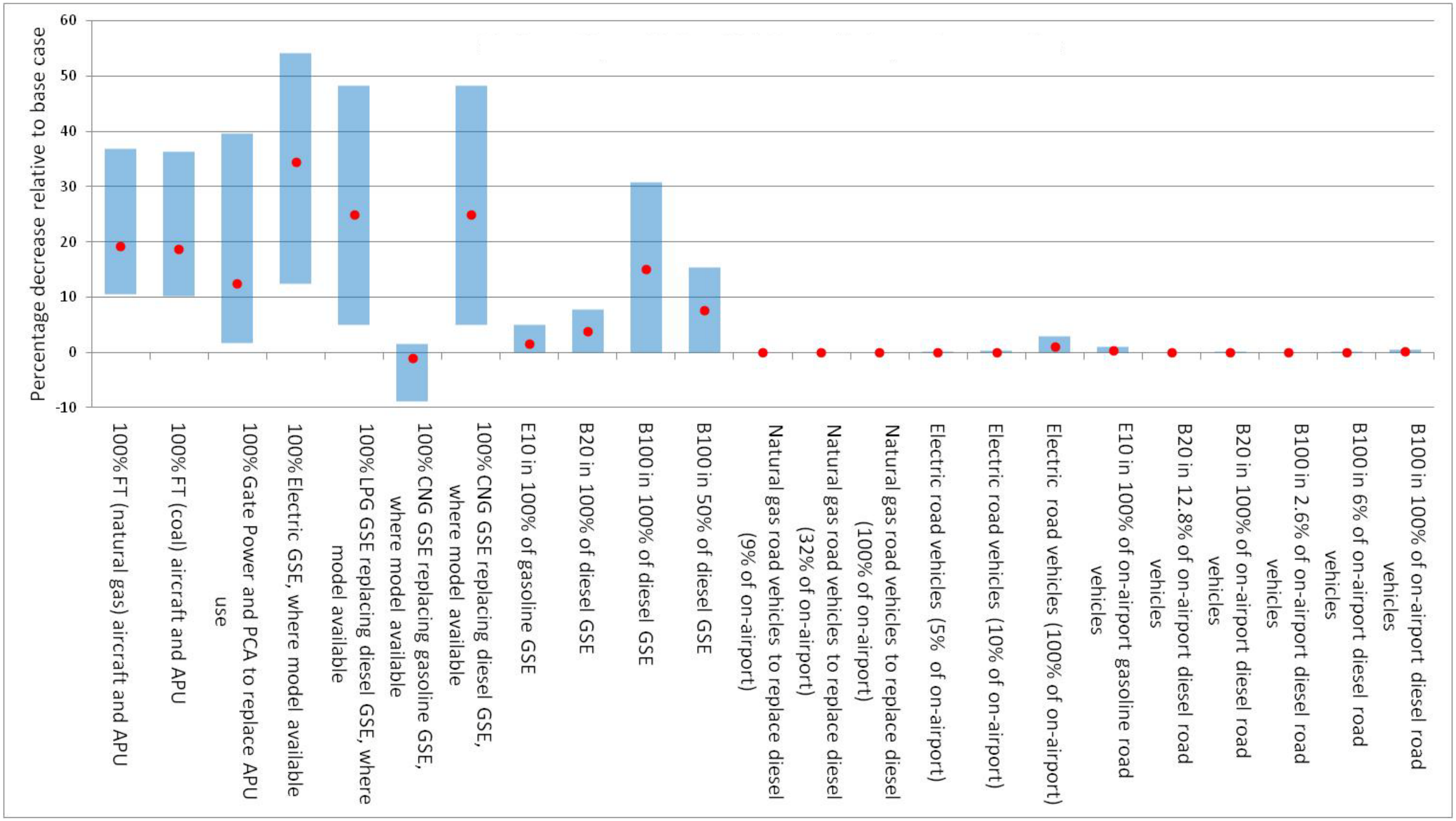


Figure 10 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Maximum Airport 24-hour 98th Percentile Impact

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.

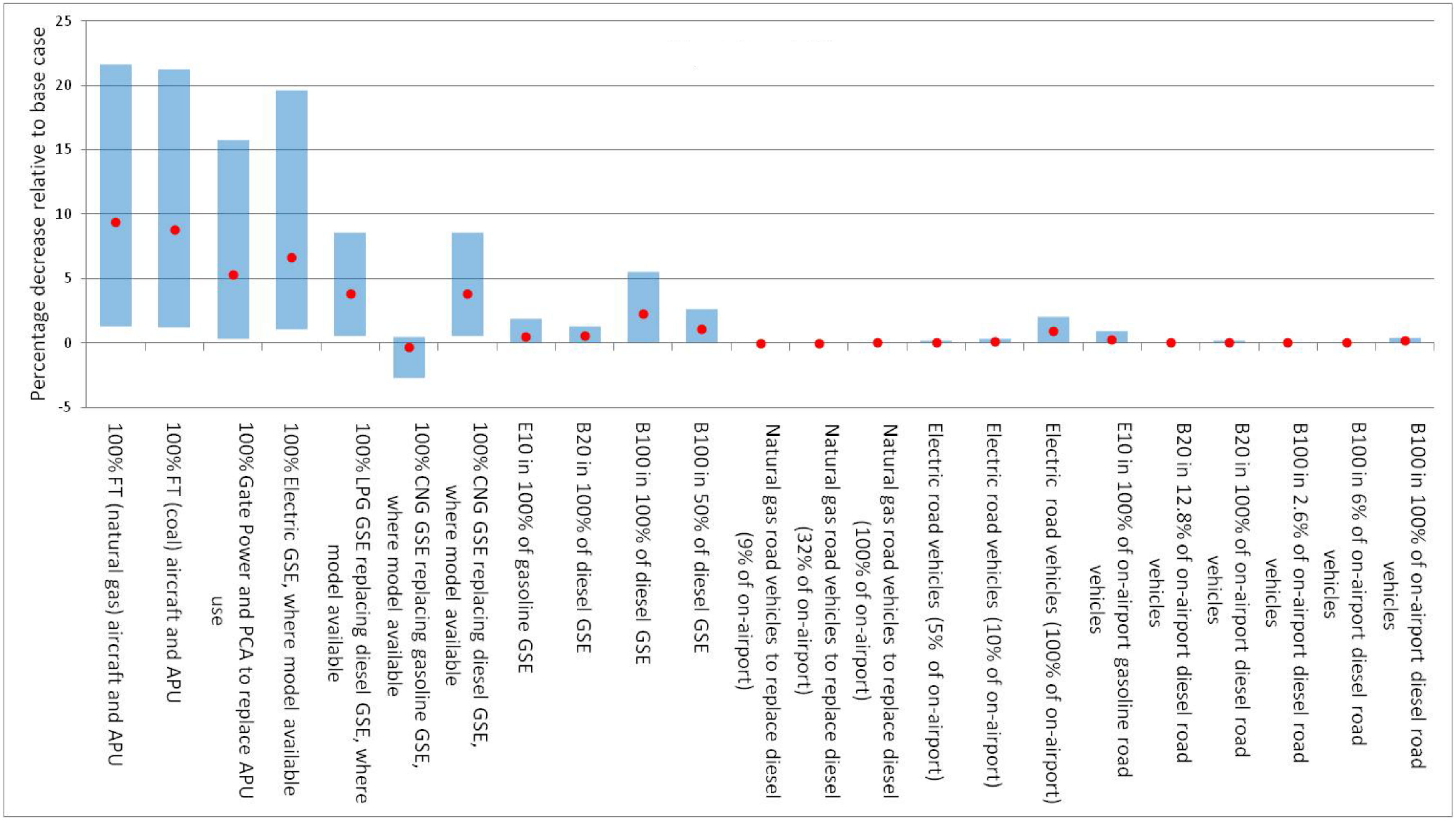


Figure 11 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Annual ROI

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.

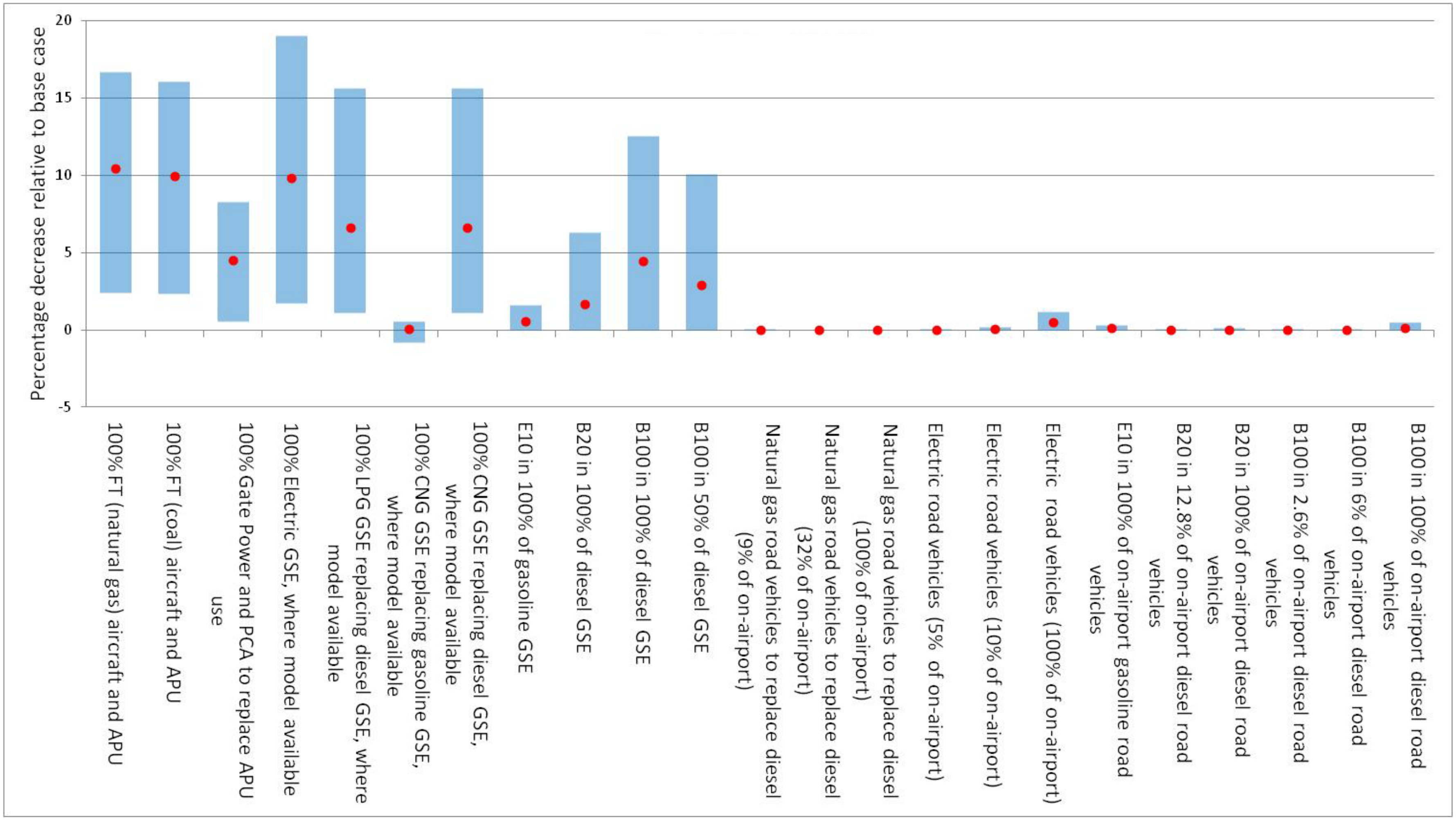


Figure 12 – Alternative Fuel Scenarios versus Base Case – Percentage Change of 24-hour 98th Percentile ROI

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.

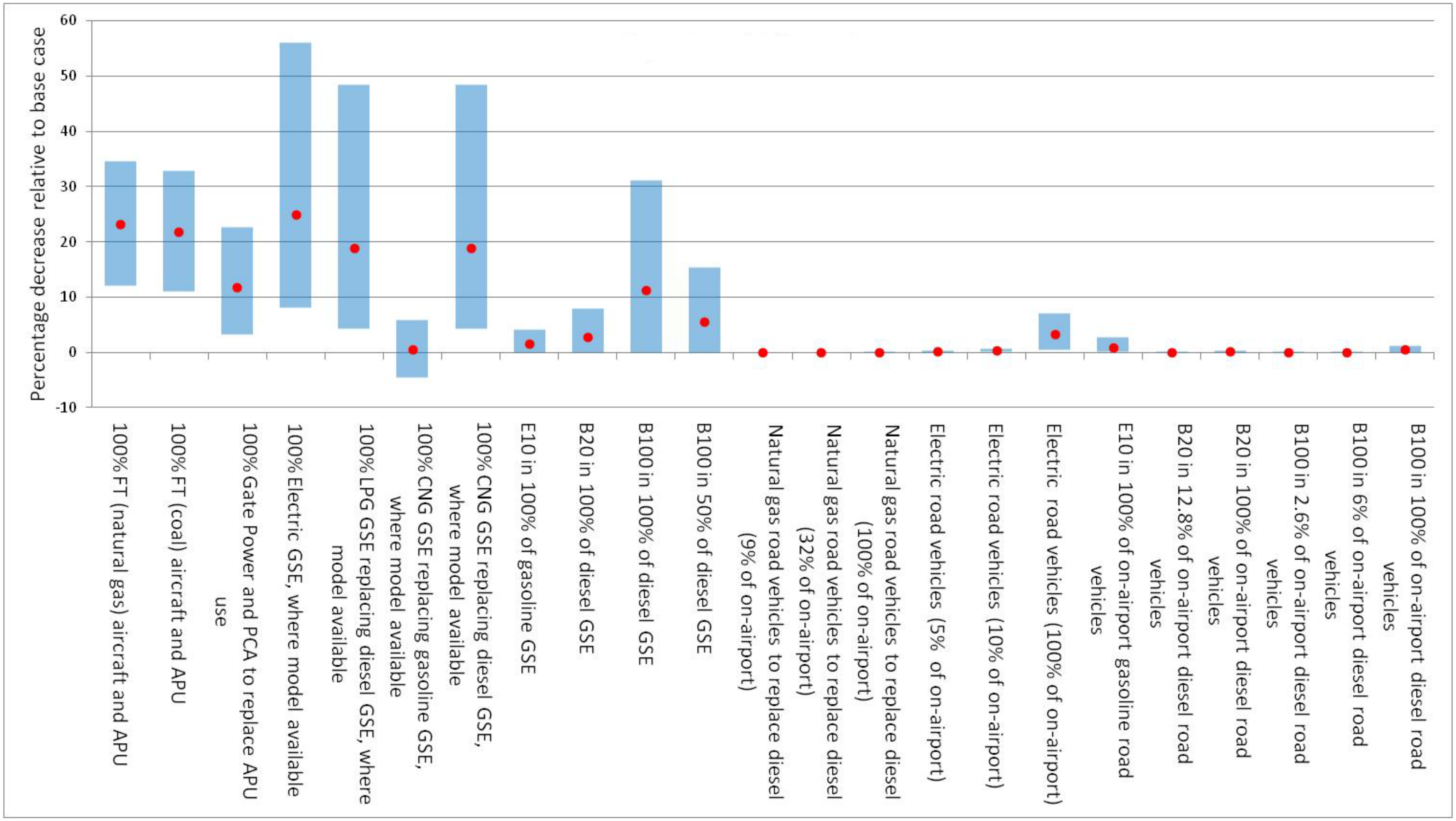


Figure 13 – Alternative Fuel Scenarios versus Base Case – Percentage Change of Annual Influence Area

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.

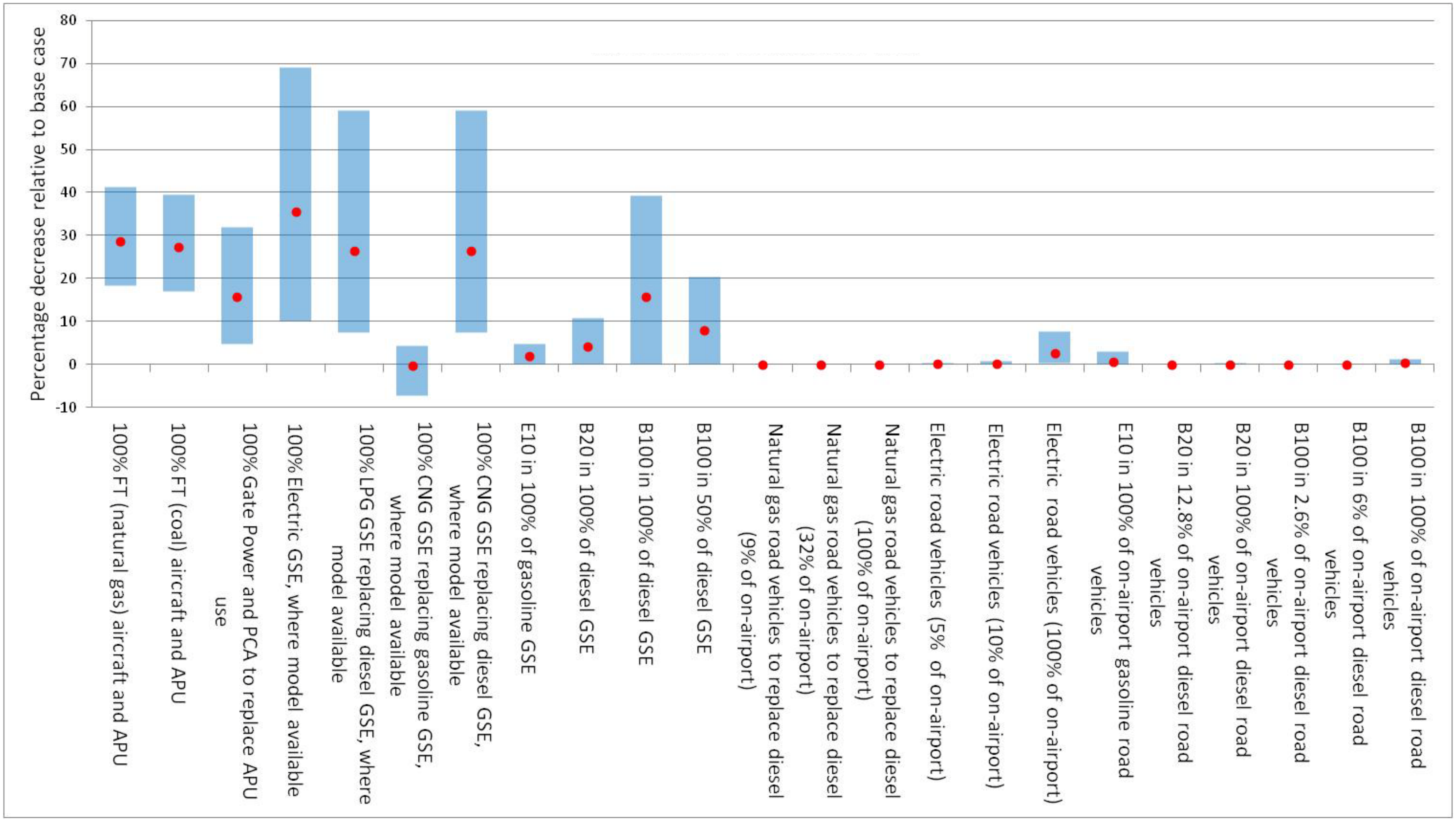


Figure 14 – Alternative Fuel Scenarios versus Base Case – Percentage Change of 24-hour 98th Percentile Influence Area

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.

Turboprop, Turboshaft, and Piston-Engine Aircraft

EDMS does not typically include $PM_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no FAA accepted emission factors for these aircraft. Therefore, these aircraft were considered separately as part of the sensitivity analysis. This section summarizes the percentage change in annual emissions for turboprop (including turboshaft) and piston-engine aircraft as a result of the alternative fuel scenarios. The alternative fuel scenarios included FT (natural gas) jet fuel for turboprop (including turboshaft) aircraft and 91/96UL AvGas for piston-engine aircraft.

Figure 15 provides the results of the alternative fuels scenarios related to turboprop (including turboshaft) and piston-engine aircraft by comparing the base case annual emissions for each aircraft type to the alternative fuel scenario emissions for the same aircraft type, which can be concluded as:

- For the five case study airports, the range of emission reductions (compared with the base case) with using of FT (50% blend with natural gas) in turboprop aircraft is between 49% and 50%, with an average of 49%.
- For the five case study airports, the range of emission reductions with using 91/96UL AvGas in piston-engine aircraft is between 97% and 98%, with an average of 97%.

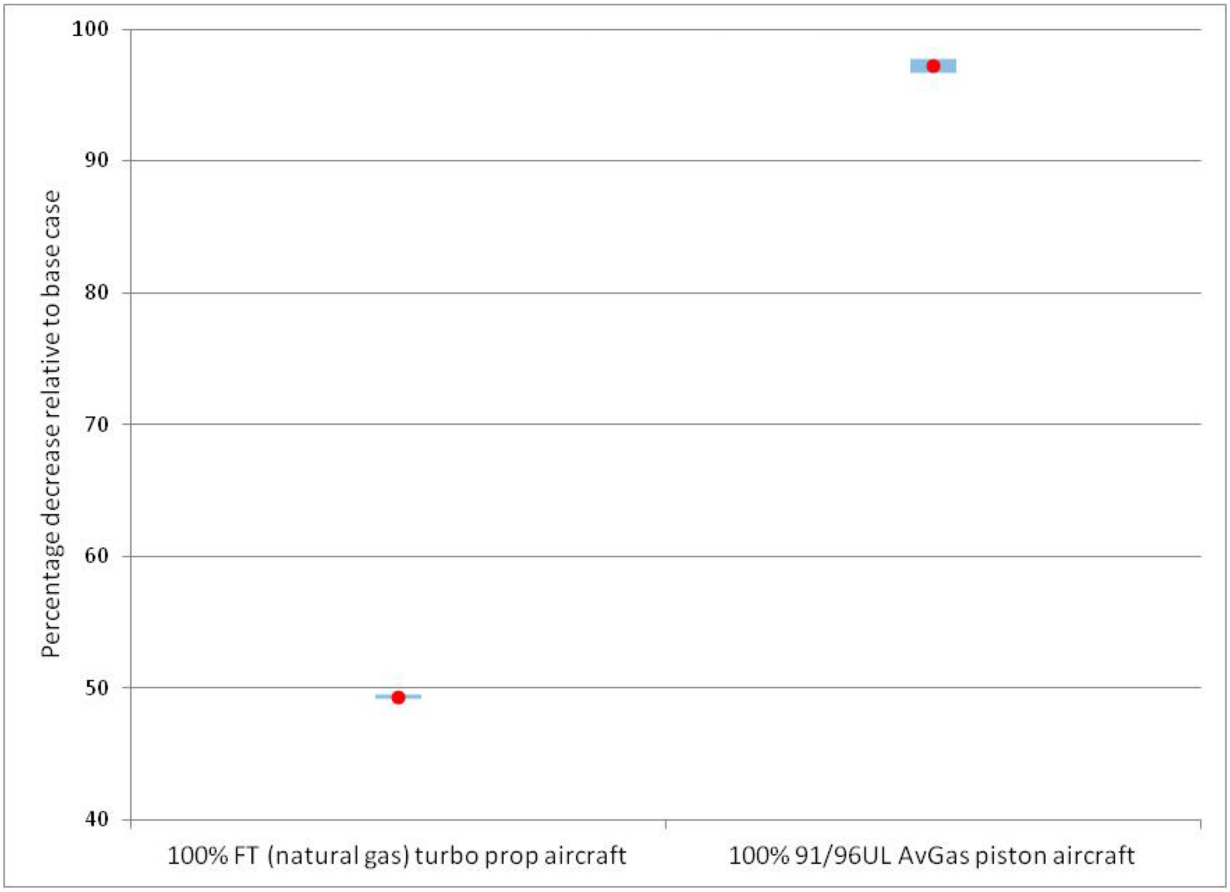


Figure 15 – Alternative Fuel Scenarios versus Base Case – Percent Change of Annual Emissions for Aircraft Type

CHAPTER 7:

CONCLUSIONS AND RECOMMENDATIONS

OVERVIEW

The ACRP 02-23 project was undertaken to assess the potential for using alternative fuels to reduce emissions and ambient concentrations of $PM_{2.5}$ at airports. The conclusions and recommendations from the ACRP 02-23 project are summarized in this chapter.

CONCLUSIONS

For those interested in emission reductions the most applicable scenarios were (listed in descending order):

- Aircraft and APU using drop-in fuels (i.e., FT fuels)
- Replacing GSE with available electric, LPG, or CNG equivalents
- Replacing diesel with biodiesel
- Reducing APU use by providing electric ground power and pre-conditioned air

For those interested in air quality improvements the most applicable scenarios were (listed in descending order):

- Replacing GSE with available electric equivalents
- Aircraft and APU using drop-in fuels (i.e., FT fuels)
- Replacing GSE with available LPG or CNG equivalents
- Reducing APU use by providing electrical ground power and pre-conditioned air
- Replacing diesel with biodiesel

For jet-fueled aircraft and APUs it can be concluded that FT jet fuels from coal and natural gas can provide substantial reductions in $PM_{2.5}$ emissions and impact. As HRJ jet fuels have a similar chemical structure this finding should be considered broadly applicable to HRJ jet fuels as well. ASTM has approved an alternative jet fuel specification in annexes to ASTM D7566 for FT and HRJ fuels blended with at least 50% conventional jet fuel. This means that, in theory, these fuels can now be produced and sold as a “drop-in” fuel for aircraft (i.e., no modifications are required to the aircraft to use this fuel). However, current availability is limited.

APU emissions can also be reduced by reducing APU use (e.g., by providing alternatives such as electrical ground power and pre-conditioned air and giving encouragement to use). However, the impact on air quality is not as substantial as it is limited to the gate area of an airport and has little impact beyond the perimeter fence. In terms of providing electrical gate power and pre-conditioned air, this is likely to need an initial high investment level, though grants through the FAA’s Voluntary Airport Low Emissions Program (VALE) can be obtained.

For GSE the best $PM_{2.5}$ emission reductions are gained when (in increasing order): gasoline, CNG, LPG or electric GSE replace diesel GSE. The cost of alternative fuels for GSE is typically either equivalent or slightly higher than conventional fuel, with the exception of the high-biofuel blends (e.g., E85 and B100), which are more expensive compared to conventional fuels. The high-biofuel blends may also create problems in terms of warranty invalidation for GSE. Alternative-fueled GSE can be bought with assistance via the FAA's VALE program.

While retrofit technology is not the subject of this report, it could be advantageous to fit equipment (e.g., particulate matter traps) to existing GSE diesel engines given the uncertainties of particulate matter emissions and to be cost-effective. Where vehicle replacement is an option, electric GSE is better when compared with other alternative fuels in terms of reducing directly emitted particulate matter (U.S. FAA, 2010a). Around the world, electric vehicles are available as replacements for baggage tugs and belt loaders. A few other specialist airside electric vehicles have been tested and there are a few makes of electric aircraft push-back tugs. However, their relatively modest capacity suggests they would not be very flexible and unable to deal with larger aircraft.

For road vehicles the best $PM_{2.5}$ emissions reductions are gained when (in increasing order) gasoline, CNG, LPG, or electric vehicles replace diesel vehicles, but these savings are limited especially in terms of their air quality impact. The cost of alternative fuels for road vehicles is typically either equivalent or slightly higher than conventional fuels, with the exception of the high-biofuel blends (e.g., E85 and B100) which are more expensive compared to conventional fuels. The high-biofuel blends may also create problems in terms of warranty invalidation for road vehicles. There is a limit to the number of road vehicles that airports can influence beyond their own fleet. However, certain strategies, such as structured parking lot charges and taxi licensing, could help to encourage use of alternative fuels in road vehicles.

No consideration is given in the ACRP 02-23 project to alternative fuels for other airport sources of $PM_{2.5}$, not listed above, such as heating plant and fire training, which generally are small in comparison to those sources discussed above. However, some airports may rely on oil- or solid-fueled power for heat generation. Oil and solid fuel plants can produce significant $PM_{2.5}$ emissions, but stack heights are normally engineered to minimize local air pollution impact. Those airports that wish to replace oil or solid fuel plants could consider either natural gas or LPG plant as low $PM_{2.5}$ emitting alternatives.

The findings for alternative fuel use in jet aircraft could be considered broadly applicable to turboprop and turboshaft aircraft. For piston-engine aircraft, alternative AvGas fuel is not yet commercially available in the U.S., but it could be in the future. Therefore, a comparison was made between 100LL (the AvGas used in the U.S.) and 91/96UL, with 91/96UL producing emission reductions in the region of 90% compared to 100LL for piston-engine aircraft.

KEY RECOMMENDATIONS

The study of air pollution and, in particular, $PM_{2.5}$ around airports is not a static subject. During the course of the ACRP 02-23 project, a number of potentially promising future sources of information, model developments, and improvements were apparent. Therefore, the following recommendations for future study have been made based on this information:

- The NASA AAFEX report was the primary source for the jet aircraft main engine and APU alternative fuel emission data. This NASA study was based on one jet engine and one APU. Further study is needed to understand the variation that the use of alternative fuels could have on other turbine engine types.

- Various alternative fuels for aircraft and non-aircraft sources of $PM_{2.5}$ were considered and discarded for a variety of reasons. One of the primary reasons was lack of suitable $PM_{2.5}$ emission data. As such, the ACRP 02-23 project could be updated when further appropriate alternative fuel $PM_{2.5}$ emissions are available (e.g., from the various PARTNER and AAFEX II projects and the resulting database of $PM_{2.5}$ emission factors and from the various ACRP projects aimed at refining APU, brake and tire wear, and GSE emissions).
- The FAA is in the process of developing the Aviation Environmental Design Tool (AEDT) combined noise and air pollution model, which will replace the FAA's EDMS in the future. Similarly, EDMS incorporates MOBILE6.2, which has been superseded by the EPA's MOVES model. The MOVES model is being developed to incorporate road and nonroad sources, as well as a number of alternative fuels. As such, it would be worth repeating the ACRP 02-23 research with these two models when they are complete.
- Further research is needed to quantify the impact that specific types of biofuel (by feedstock, blend, and engine type) will have on primary and volatile (i.e., "secondary") particulate matter emissions.

BIBLIOGRAPHY

AAFEX (2010), Project Summary, Conference Proceedings, October 2010

Aatmeeyata, D. S. and Kaul, M. S. (2009), *Traffic generated non-exhaust particulate emissions from concrete pavement: A mass and particle size study for two-wheelers and small cars*, *Atmospheric Environment* Volume 43, pp. 5691–5697

ACRP (2008), *Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data*; Airport Cooperative Research Program, Transportation Research Board

ACRP (2009), *ACRP Report 11: Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories*, Transportation Research Board, http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_011.pdf accessed May 2011

ACRP (2011a), *Project 02-17: Measuring PM Emissions from Aircraft, Auxiliary Power Units, Tires and Brakes*, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2788 accessed January 2011

ACRP (2011b), *ACRP Report 46: Handbook for Analyzing the Costs and Benefits of Alternative Aviation Turbine Engine Fuels at Airports*, Transportation Research Board, http://onlinepubs.trb.org/onlinepubs/acrp/acrp_rpt_046.pdf accessed June 2011

AEA (2008), *Road Transport Emissions from Biofuel Consumption in the UK*, AEA Technology, Report Ref. AEAT/ENV/R/2662 for The Department for Environment, Food and Rural Affairs, Welsh Assembly Government, the Scottish Executive and the Department of the Environment for Northern Ireland, http://uk-air.defra.gov.uk/reports/cat15/0901151441_NAEI_Road_Transport_Biofuels_report_2008_v1.pdf

AEA (2009), *An Airside Vehicle Strategy Assessment for Heathrow, Final Report*, Final Report Issue Number 3 for BAA plc, AEA Technology, Project Ref. ED46237, October 2009

Anderson, et al., (2011), *Alternative Aviation Fuel Experiment (AAFEX)*, NASA/TM-2011-217059, National Aeronautics and Space Administration, Langley Research Center, February 2011

AQEG (2005), *Particulate matter in the United Kingdom,* Air Quality Expert Group. Defra, London. ISBN 0-85521-143-1, Defra Publication PB10580. http://www.defra.gov.uk/environment/airquality/publications/particulate-matter/index.htm (accessed August 2010)

Argonne (2005), *Well-to-Wheels Analysis of Advanced Fuel/Vehicle Systems – A North American Study of Energy Use, Greenhouse Gas Emissions, and Criteria Pollutant Emissions*, Argonne National Laboratory

ASTM (2010), *Standard Specification for Aviation Turbine Fuel*, ASTM International, West Conshohocken, PA, ASTM D1655-10

ASTM (2011), *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*, ASTM International, West Conshohocken, PA, ASTM D7566-11a, www.astm.org/Standards/D7566.htm (accessed August 2011)

ATL (2010), *Hartsfield-Jackson Atlanta International Airport 2008 Air Emissions Inventory*, January 28, 2010

Auer, A. H. (1978) *Correlation of Land Use and Cover with Meteorological Anomalies,* Journal of Applied Meteorology, pp. 636-643

BAA (2007), *Heathrow Local Air Quality Action Plan 2007-2011*, BAA Heathrow, http://www.heathrowairport.com/assets//B2CPortal/Static%20Files/Action_Plan.pdf

Beardsley, M. (2006), *Fuels & Fuel Effects in MOVES2006*, EPA Office of Transportation & Air Quality presentation to FACA Meeting, August 2008

Beyersdorf, A. and Anderson, B. (2009), *An Overview of the NASA Alternative Aviation Fuel Experiment (AAFEX)*, TAC-2 Proceedings, Aachen and Maastricht, June 2009

BCAA (2006), *Task 5: Investigating Air Emission Impacts on the Community – Particle Deposition from Airport Activities. Final Report*, Broward County Aviation Authority (BCAA), Clean Airport Partnership, Inc., and Environmental Consulting Group, Inc., November 2006

Bulzan, D., Anderson, B. and Wey, C. (2010), *Gaseous and Particulate Matter Emissions Results of the NASA AAFEX*. Proceedings of the ASME Turbo Expo 2010: Power for Land, Sea and Air, June 2010, Glasgow, Scotland

CAAFI (2010), *Glossary*, http://www.caafi.org/resources/glossary.html (as of August 2010)

CARB (2006a), *EMFAC2007 Emissions Model User's Guide*, November 2006, http://www.arb.ca.gov/msei/onroad/latest_version.htm

CARB (2006b), *OFFROAD2007 Emissions Model User's Guide*, November 2006, http://www.arb.ca.gov/msei/offroad/offroad.htm

CDM (in progress), *Airport Ground Support Equipment (GSE) Inventory and Emission Reduction Strategies*, ACRP Project 02-16, http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2787

Census (2000), U.S. 2000 Census http://www.census.gov/statab/ccdb/cit1040a.txt

Champagne, D. (1971), *Standard Measurement of Aircraft Gas Turbine Exhaust Smoke*; American Society of Mechanical Engineers

Cheng, M-D., Corporan, E., DeWitt, M. J. and Landgraf, D. (2009), "Emissions of Volatile Particulate Components from Turboshaft Engines Operated with JP-8 and Fischer-Tropsch Fuels," *Aerosol and Air Quality Research*, Vol. 9 (2), pp. 237-256

Corporan, E. and Cheng, M-D. (2010), *Emissions Characteristics of Military Helicopter Engines with JP-8 and Fischer–Tropsch Fuels*, *Journal of Propulsion and Power*, Vol. 26 (2), March-April 2010, pp.317-324

Corporan, E. et al., (2007), *Emissions Characteristics of a Turbine Engine and Research Combustor Burning a Fischer-Tropsch Jet Fuel*, *Energy and Fuels*, 21, pp. 2615-2626

CSSI, Inc. (2009), *Emissions and Dispersion Modeling System (EDMS) User's Manual Rev. 7*, Federal Aviation Administration

Dieselnet (2010), *United States emissions standards for nonroad diesel engines*, (available at online information service http://www.dieselnet.com/standards/us/nonroad.php), summarizing Code of Federal Regulations (CFR) Title 40 *Protection of Environment*" Part 89 "*Control of emissions from new and in-use nonroad compression-ignition engines.* (accessed 2010)

Dodson, R., Houseman, E.A., Morin, B. and Levy, J. (2009), *An Analysis of Continuous Black Carbon Concentrations in Proximity to and Airport and Major Roadways*, *Atmospheric Environment,* Vol 43 pp. 3764-3773

Energy Efficiency News (2009), *US airport tests wind-powered electric vehicle*, http://www.energyefficiencynews.com/power-generation/i/2074/ (accessed August 2010)

ENVIRON (2008), *Teterboro Airport Detailed Air Quality Evaluation, Project #08-14159A Final Report*

European Aviation Safety Agency (2009), Specifications attached to the *Invitation to Tender: Studying, sampling and measuring of aircraft particulate emissions II – SAMPLE II*

EEA (2005), *EMEP/CORINAIR Emission Inventory Guidebook – 2006*, European Environment Agency (EEA) technical report No 11/2006, http://reports.eea.europa.eu/EMEPCORINAIR4/en/

EEA (2009, 2007 and 2005), *CORINAIR Emissions Inventory Guidebook*, European Environment Agency, available from www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2009

EPRI (2007*), Environmental Assessment of Plug-In Hybrid Electric Vehicles: Volume 1: Nationwide Greenhouse Gas Emissions*, Electric Power Research Institute, 2007

Fanning, E., Yu, R.C., Lu, R. and Froines, J. (2007), *Monitoring and Modeling of Ultra-fine Particles and Black Carbon at the Los Angeles International Airport*, Report to CARB and CalEPA, ARB Contract #04-325

Finneran, M., *Chicken Fat Biofuel: Eco-friendly Jet Fuel Alternative?* March 25, 2011, http://www.nasa.gov/topics/aeronautics/features/aafex2.html

FOCA (2007a), *Aircraft Piston-Engine Emissions Summary Report*, Report 33-05-003, Federal Office of Civil Aviation (FOCA), Switzerland, June 2007

FOCA (2007b), *Aircraft Piston-Engine Emissions Summary Report Appendix 4: Nanoparticle Measurements and Research for Cleaner AvGas*, Federal Office of Civil Aviation (FOCA), Switzerland (2007)

Gaffney, J.S. and Marley, N.A. (2009), *The impacts of combustion emissions on air quality and climate – From coal to biofuels and beyond*, *Atmospheric Environment* 43, pp. 23–36

GAL (2009), *London Gatwick Airport: Air Quality Management Action Plan 2009-2011*, Gatwick Airport Limited http://www.gatwickairport.com/Documents/business_and_community/Misc/Air_Quality_Action_Plan_Final.pdf

Goodrich, M. (2009), *Biofuel for Jets Could Cut Carbon Emissions Over 80 Percent*, Michigan Tech news media, May 2009; http://www.admin.mtu.edu/urel/news/media_relations/884/

Grace, J., 2011. *Air Force Tells Biofuels Industry to "Bring It,"* National Defense, January 2011. http://www.nationaldefensemagazine.org/archive/2011/January/Pages/AirForceTellsBiofuelsIndustrytoBringIt.aspx

Hileman, Wong, Ortiz, et al., (2008), *The feasibility and potential environmental benefits of alternative fuels for commercial aviation*, 26th International Congress of the Aeronautical Sciences

Hileman, J. I. et al., (2009), *Technical Report: Near-Term Feasibility of Alternative Jet Fuels*, http://www.rand.org/pubs/technical_reports/2009/RAND_TR554.pdf

Hill J, Nelson E, Tilman D, Polasky S and Tiffany D (2006), *Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels, Proc Natl Acad Sci U S A,* 2006 July 25; 103(30): pp.11206–11210

Hu, S., Fruin, S., Kowaza, K., Mara, S., Winer, Al, and Paulson, S. (2009), *Aircraft Emission Impacts in a Neighborhood Adjacent to A General Aviation Airport in Southern California. Environmental Science and Technology*, Vol. 43 pp. 8039-8045

Hurley, C. (1993), *Smoke Measurements Inside a Gas Turbine Combustor, Proceedings of the 29th Joint Propulsion Conference and Exhibit Monterey*

IATA (2010), *Fact Sheet on Alternative Fuels,* http://www.iata.org/pressroom/facts_figures/fact_sheets/Pages/alt_fuels.aspx (accessed September, 2010)

ICAO (1993), *International standards and recommended practices*, International Civil Aviation Organization, *Environmental Protection,* Annex 16, Volume II Aircraft engine emissions, 2nd edition

ICAO (2007), *Airport Air Quality Guidance Manual Preliminary Edition 2007*, http://www.icao.int/icaonet/dcs/9889/9889_en.pdf, International Civil Aviation Organization

ICAO (2010), Engine Exhaust Emissions Databank, Available at http://www.caa.co.uk/default.aspx?catid=702, (last accessed December 2011)

ICAO (2011), *Airport Air Quality Guidance Manual First Edition 2011*, Doc 9889, ISBN 978-92-9231-862-8, International Civil Aviation Organization

John, W. (2006), *Revisions to Smoke Number Data in Emissions Databank,* QinetiQ UK, February 2006

JNC (2006), *Final Report to the European Commission for the preparation of the 2005 review of Directive 98/70/EC as amended by Directive 2003/17/EC relating to the quality of gasoline and diesel fuels,* Report prepared for the European Commission, Joint Research Centre (Ispra), February 2006

Kavalov, B. and Peteves, S. D. (2005), *Status and perspectives of biomass-to-liquid fuels in the European Union*, Report prepared for the European Commission Directorate-General Joint Research Centre

Kinsey, J. (2009), *Characterization of Emissions from Commercial Aircraft Engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3*, U.S. Environmental Protection Agency

Kojima, M. and Johnson, T. (2005), *Potential for biofuels transport in developing countries*, Report for Energy Sector Management Assistance Programme (ESMAP), UNDP and The World Bank, Washington D.C.,U.S.A., www.esmap.org/filez/pubs/31205BiofuelsforWeb.pdf

Krahl, J. et al., (2009), *Comparison of exhaust emissions and their mutagenicity from the combustion of biodiesel, vegetable oil, gas-to-liquid and petrodiesel fuels, Fuel,* Volume 88, Issue 6 pp. 1064-1069

Lapuerta, M., Armas, O., Ballesteros, R. and Fernandez, J. (2005), *Diesel emissions from biofuels derived from Spanish potential vegetable oils*, *Fuel,* Volume 84, pp. 773–780

Lapuerta, M., Armas, O. and Rodriguez-Fernandez, J. (2008), *Effect of biodiesel fuels on diesel engine emissions*, *Progress in Energy and Combustion Science* Volume 34, pp. 198–223

LAS (2010), *Southern Nevada Supplemental Airport Environmental Impact Statement Air Quality Technical Report* (unpublished), May 31, 2010

LAS (2011), *Estimated Emissions* spreadsheet provided by Mark E. Silverstein with stationary source emissions data, LAS, November 2011

Lau, C. R., Stromgren, J. T. and Green, D. J. (2010), *2010 TRB ACRP Synthesis 21: Airport Energy Efficiency and Cost Reduction, A Synthesis of Airport Practice*

Lobo, P., Whitefield, P.D., Hagen, D.E., Rye, L.J., Blakey, S., Wilson, C.W., Williams, P., Christie, S., Raper, D., Uryga-Bugajska, I. and Pourkashanian, M. (2011), *SAE E31 Methodology Development and Association PM Emissions Characteristics of Aircraft APUs burning Conventional and Alternative Aviation Fuels. The PARTNER Project 34 Final Report.* PARTNER-COE-2011-005, July 2011

Massport (2008), *2008 Boston Logan International Airport Environmental Data Report*, Massachusetts Port Authority (Massport)

Massport (2010), *Air Quality Monitoring Study Baseline Year Report, Logan International Airport*, Massachusetts Port Authority (Massport), August 2010

MHT (2009), *Manchester-Boston Regional Airport 2007 Air Emissions Inventory*, February 4, 2009

Miake-Lye, R. C. et al., (2009), *Effects of Alternative Fuels on Hydrocarbon and Particle Emissions from Aircraft Engines,* TAC-2 Proceedings, June 22 – 25, 2009, Aachen and Maastricht

Missouri University of Science and Technology (in progress), *Measuring PM Emissions from Auxiliary Power Units, Tires and Brakes,* ACRP Project 02-17, http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2788

Missouri University of Science and Technology (2011a), PARTNER Project 20 Emissions Characteristics of Alternative Aviation Fuels website: http://web.mit.edu/aeroastro/partner/projects/project20.html (accessed April 2011)

Missouri University of Science and Technology (2011b), PARTNER Project 9 Measurement of Emissions website: http://web.mit.edu/aeroastro/partner/projects/project9.html (accessed April 2011)

Missouri University of Science and Technology (2011c), PARTNER Project 17 Alternative Fuels website: http://web.mit.edu/aeroastro/partner/projects/project17.html (accessed April 2011)

MOU (2008), *Memorandum of Understanding Between the Attorney General of the State of California and the San Diego County Regional Airport Authority Regarding the San Diego International Airport Master Plan*, May 5, 2008

Muncrief, R. L., Cruz, M. D., Harold, M. P. and Rooks, C. W. (2007), *Combining Biodiesel and EGR for Low-Temperature NOx and PM Reductions*, University of Houston Department of Chemical and Biomolecular Engineering, paper presented at Diesel Engine-Efficiency and Emissions Research conference, Detroit, Michigan

Nam, E. and Srivastava, S. (2006), *Brake and Tire Emissions in MOVES*, EPA Office of Transportation & Air Quality presentation to FACA Meeting, August 2008

Natural Gas Vehicles for America (2011), *Facts about Natural Gas,* http://www.ngvamerica.org/about_ngv/ website accessed June 2011

Norton, P. et al., (1998), *Emissions from Trucks using Fischer-Tropsch Diesel Fuel,* Paper presented at International Fall Fuels and Lubricants Meeting and Exposition, San Francisco, California

Petzold, A. et al., (2005), *Particle emissions from aircraft engines – a survey of the European project PartEmis*, Meteorologische Zeitschrift

Petzold, A., Marsh, R. et al., (2009), *Study on sampling and measurement of aircraft particulate emissions SAMPLE – Final Report,* European Aviation Safety Agency

PHL (2010), *Philadelphia International Airport Capacity Enhancement Program Air Quality Technical Report*, August, 2010

PPC (2010), *Working Plan for Airport Cooperative Research Program Project 02-23 Alternative Fuels as a Means to Reduce $PM_{2.5}$ Emissions at Airports*, PPC, July 2010

Ratliff, G. et al., (2009), *PARTNER Project 15 – Aircraft Impacts on Local and Regional Air Quality in the United States*, Massachusetts Institute of Technology

Resources for the Future (2010), *Energy, Greenhouse Gas, and Economic Implications of Natural Gas Trucks*, http://www.rff.org/RFF/Documents/RFF-BCK-Krupnick-NaturalGasTrucks.pdf Krupnick A, accessed June 2010

RIAC (2009), *T.F. Green 2008 Air Emissions and Greenhouse Gas Inventory,* Rhode Island Airport Corporation (RIAC), March 2009

RI DEM (2008), *Characterization of Ambient Air Toxics in Neighborhoods Abutting T.F. Green Airport and Comparison Sites, Final Report*, Rhode Island Department of Environmental Management (RI DEM), Office of Air Resources, http://www.dem.ri.gov/programs/benviron/air/pdf/tfgfinrp.pdf, April 2008

Ristovski, Z. D., Morawska, L., Bofinger, N. D. and Hitchins, D. J. (1998), *Submicrometer and Supermicrometer Particulate Emission from Spark-Ignition Vehicles*, *Environmental Science and Technology* Vol. 9, pp 3845 – 3852

Smith Electric Vehicles (2010), *Babcock Airports,* http://www.smithelectricvehicles.com/casestudies_babcock.asp (accessed August 2010)

SAE (2004), E-31 Aircraft Exhaust Emissions Measurement Committee, *Nonvolatile Exhaust Particle Measurement Techniques (AIR 5892 Rev A)*, Society of Automotive Engineers (SAE), SAE International

SAN (2009), *San Diego County Regional Airport Authority Air Quality Management Plan* (Appendix A – Criteria Pollutant & Greenhouse Gases Baseline Emissions Inventory), Final Draft, Prepared by C&S Companies, KB Environmental Sciences, Inc. and Synergy Consultants, Inc., for San Diego County Regional Airport Authority, http://www.san.org/documents/AQMP/SAN%20AQMP%20Draft%20Final%20Report.pdf, November 2009

SCAQMD (2000a), *Air Monitoring Study in the Area of Los Angeles International Airport*, South Coast Air Quality Management District (SCAQMD)

SCAQMD (2000b), *General Aviation Airport Air Monitoring Study, Draft Report*, South Coast Air Quality Management District (SCAQMD), February 2010

TNO (2004), *Compatibility of pure and blended biofuels with respect to engine performance, durability and emissions: A literature review*, Report prepared for the Dutch Ministry for Spatial Planning, Housing and the Environment, December 2004

TreeHugger (2008), *Free Hybrid Electric Buses at Tokyo's Haneda Airport,* (http://www.treehugger.com/files/2008/08/hybrid-electric-bus-tokyo.php (accessed August 2010)

Unal, A. et al., (2005), Airport-Related Emissions and Impacts on Air Quality: Application to the Atlanta International Airport, *Atmospheric Environment* Vol 39 pp. 5787-5798

Underwood, B. (2007), *Revised Emissions Methodology for Heathrow Base Year 2002,* Report to the UK Department for Transport, AEAT/ENV/R/2193 Final (November 2007) http://webarchive.nationalarchives.gov.uk/+/http://www.dft.gov.uk/consultations/archive/2008/heathrowconsultation/technicalreports/emissionmethodology.pdf

Underwood, B. Y., Walker, C. T. and Peirce M. J. (2010), *Heathrow Airport emission inventory 2008/9*, AEA, AEAT/ENV/R/2906 Issue 1

Unique (2004), *Aircraft Ground Handling Emissions at Zurich Airport Methodology and Emission Factors, 2004*, Unique (Flughafen Zürich AG), http://www.zurich-airport.com/desktopdefault.aspx/tabid-580/

Unique (2006), *Ground Power Unit (GPU) Exhaust Emissions at Zurich Airport, 2006*, Unique (Flughafen Zürich AG), http://www.zurich-airport.com/desktopdefault.aspx/tabid-580/

U.S. Air Force (2002), *Aircraft/Auxiliary Power Units/Aerospace Ground Support Equipment Emission Factors*, IERA-RS-BR-SR-2003-0002, October 2002

U.S. DOE (2009), U.S. Energy Information Administration, *Annual Energy Review 2009,* Report No. DOE/EIA-0384(2009), Release Date August 2010. Available at: http://www.eia.gov/emeu/aer/petro.html (accessed August 2010)

U.S. DOE (2010), Alternative Fuels website: www.afdc.energy.gov/afdc/ U.S. Department of Energy (DOE) (accessed August 2010)

U.S. DOE (2011), *Clean Cities Alternative Fuel Price Report*, U.S. Department Of Energy, January 2011. Available at http://www.afdc.energy.gov/afdc/pdfs/afpr_jan_11.pdf (accessed March 2011)

U.S. Energy Information Administration (2010), *Annual Energy Review 2009,* Report No. DOE/EIA-0384 (2009), http://www.eia.gov/emeu/aer/petro.html (Release Date August 19, 2010)

U.S. Energy Information Administration (2011), *Annual Energy Outlook 2011*, April 26, 2011, Report Number: DOE/EIA-0383(2011)

U.S. EPA (1980), *AP-42 Supplement 10 for Compilation of Air Pollutant Emission Factors, Third edition,* U.S. Environmental Protection Agency (EPA), February 1980

U.S. EPA (1999), *Technical Support Document for Development of Airport Ground Support Equipment Emission Reductions*, U.S. Environmental Protection Agency, EPA-420-R-99-007, May 1999

U.S. EPA, 2002a) AirData, 2002 Emissions Inventory for Metropolitan Statistical Area. Available at http://www.epa.gov/oar/data/geosel.html (accessed August 2011)

U.S. EPA (2002b), *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*, U.S. Environmental Protection Agency, Draft Technical Report, EPA420-P-02-001

U.S. EPA (2003a), *MOBILE6.1 Particulate Emission Factor Model Technical Description, Final Report*, U.S. Environmental Protection Agency, EPA420-R-03-001, M6.PM.001, January 2003

U.S. EPA (2003b), *User's Guide to MOBILE6.1 and MOBILE6.2 Mobile Source Emission Factor Model*, U.S. Environmental Protection Agency, EPA420-R-03-010, August 2003

U.S. EPA (2004a), *Clean Air Nonroad Diesel – Tier 4 Final Rule*, U.S. Environmental Protection Agency, http://www.epa.gov/nonroad-diesel/2004fr.htm

U.S. EPA (2004b), *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression-Ignition*, U.S. Environmental Protection Agency, EPA420-P-04-009

U.S. EPA (2005), *User's Guide for the Final NONROAD2005 Model*, U.S. Environmental Protection Agency, EPA420-R-05-013, December 2005

U.S. EPA (2008), *NONROAD2008a*, U.S. Environmental Protection Agency, http://www.epa.gov/OMS/nonrdmdl.htm (accessed August 2010)

U.S. EPA (2009a), *Nonroad Diesel Equipment*, U.S. Environmental Protection Agency, http://www.epa.gov/nonroad-diesel/index.htm (accessed August 2010)

U.S. EPA (2009b), *Development of Emission Rates for Heavy-Duty Vehicles in the Motor Vehicle Emissions Simulator (Draft MOVES2009)*, U.S. Environmental Protection Agency, Draft Report Ref. EPA-420-P-09-005

U.S. EPA (2009c), *Draft Motor Vehicle Emission Simulator (MOVES) 2009 Software Design and Reference Manual*, U.S. Environmental Protection Agency, EPA-420-B-09-007, March 2009

U.S. EPA (2009d), *Suggested Nationwide Average Fuel Properties*, U.S. Environmental Protection Agency, EPA-420-B-09-018, April 2009

U.S. EPA (2010a), *Green Book Non-attainment Areas for Criteria Pollutants*, U.S. Environmental Protection Agency http://www.epa.gov/oar/oaqps/greenbk/index.html (as of September 7, 2010)

U.S. EPA (2010b), *AirData: Access to Air Pollution Data*, U.S. Environmental Protection Agency http://www.epa.gov/oar/data/ (as of September 7, 2010)

U.S. EPA (2010c), *Modeling and Inventories*, U.S. Environmental Protection Agency, http://www.epa.gov/otaq/models.htm (as of August 2010)

U.S. EPA (2010d), *Prevention of Significant Deterioration for $PM_{2.5}$ – Increments, Significant Impact Levels and Significant Monitoring Concentrations*, Federal Register: October 20, 2010, Volume 75, Number 202

U.S. EPA (2010e), *Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression-Ignition*, U.S. Environmental Protection Agency, EPA-420-R-10-018, NR-009d, July 2010

U.S. EPA (2010f), *Motor Vehicle Emission Simulator (MOVES) User Guide for MOVES2010a*, U.S. Environmental Protection Agency, EPA-420-B-10-036, August 2010

U.S. EPA (2010g), *Compilation of Air Pollutant Emission Factors,* U.S. Environmental Protection Agency, AP-42 available from the Clearinghouse for Inventories & Emissions Factors, www.epa.gov/ttn/chief (accessed August 2010)

U.S. EPA (2011a), *National Ambient Air Quality Standards (NAAQS)*, http://www.epa.gov/air/criteria.html (accessed May 2011)

U.S. EPA (2011b), *Policy Assessment for the Review of the Particulate MatterNational Ambient Air Quality Standards*, U.S. Environmental Protection Agency, EPA 452/R-11-003, April 2011, http://www.epa.gov/ttnnaaqs/standards/pm/data/20110419pmpafinal.pdf

U.S. EPA (2011c), *Green Book Non-attainment Areas for Criteria Pollutants*, U.S. Environmental Protection Agency http://epa.gov/oaqps001/greenbk/rindex.htmlhttp://www.epa.gov/oar/oaqps/greenbk/index.html (as of August 25, 2011)

U.S. FAA (2006a), *Order 1050.1E Change 1: Environmental Impacts, Policies and Procedures*, U.S. Federal Aviation Administration (FAA)

U.S. FAA (2006b), *Inherently Low Emission Airport Vehicle Pilot Program Final Report*, U.S. Federal Aviation Administration Office of Airports Community and Environmental Needs Division, http://www.faa.gov/airports/environmental/vale/media/ileav_report_final_2005.pdf

U.S. FAA (2009), *Emissions and Dispersion Modeling System (EDMS) Version 5.1.2*, Technical Manual, November 2009

U.S. FAA (2009a), *Emissions and Dispersion Modeling System (EDMS) User's Manual*, Version 5.1.2, November 2009

U.S. FAA (2010a), *Voluntary Airport Low Emission Program Technical Report*, Version 6, Federal Aviation Administration

U.S. FAA (2010b), *Vale Program Grant Summary FY2005–FY2010*, Federal Aviation Administration, http://www.faa.gov/airports/environmental/vale/media/VALE_grant_summary.pdf, September 2010

U.S. FAA (2010c), *Philadelphia International Airport Capacity Enhancement Program Final Environmental Impact Statement and Draft General Conformity Determination*, Federal Aviation Administration, April 2010

U.S. FAA (2010d), *Passenger Boarding (Enplanement) and All-Cargo Data for U.S. Airports,* Federal Aviation Administration, http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/ (accessed October 2010)

U.S. FAA (2010e), *FAA 5010 Airport Data*, Federal Aviation Administration, http://www.faa.gov/airports/airport_safety/airportdata_5010/menu/index.cfm (accessed October 2010)

U.S. FAA (2010f), *FAA Aviation Performance Metrics*, Federal Aviation Administration, http://aspm.faa.gov/ (site updated Nov 10)

U.S. FAA (2010g), *Voluntary Airport Low Emissions Program (VALE),* Federal Aviation Administration, http://www.faa.gov/airports/environmental/vale/ (accessed August 2010)

U.S. FAA (2010h), *Voluntary Airport Low Emissions Program Technical Report*, Version 7, December 2nd, 2010, http://www.faa.gov/airports/environmental/vale/media/vale_techreport_v7.pdf (accessed July 2011)

U.S. FAA and RIAC (2010), *T.F. Green Airport Improvement Program Environmental Impact Statement: Air Quality Technical Report*, U.S. Environmental Protection Agency and Rhode Island Airport Corporation, July 2010

Volpe (2010), Evaluation *of methods for computing aircraft particulate matter (PM) emissions*, http://www.volpe.dot.gov/air/aq-faa.html (accessed September 2010)

Wang, W. G., Lyons, D. W., Clark, N. N., Gautam, D. M. and Norton, P. M. (2000), "*Emissions from Nine Heavy Trucks Fueled by Diesel and Biodiesel Blend without Engine Modification," Environ. Sci. Technol.* Vol 34, pp 933-939

Wayson, R., Fleming, G., Kim, B. (2003), *A Review of Literature on Particulate Matter Emissions from Aircraft*; DTS-34-FA22A-LR1, Federal Aviation Administration

Wayson, R; Fleming, G; Iovinelli, R. (2009), "Methodology to Estimate Particulate Matter Emissions from Certified Commercial Aircraft Engines," *Journal of the Air and Waste Management Association*

Webb, S., Whitefield, P.D., Miake-Lye, R.C., Timko, M.T., and Thrasher, T.G. (2008), *Research Needs Associated with Particulate Emissions at Airports*, ACRP Report 6, U.S. TRB, http://144.171.11.107/Main/Public/Blurbs/160036.aspx

Westerdahl, D., Fruin, S.A., Fine, P.L., and Sioutas, C. (2008), *The Los Angeles International Airport as a Source of Ultra-fine Particles and Other Pollutants to Nearby Communities*, *Atmospheric Environment*, Vol. 42 pp. 3143-3155

Whitefield, P.D. et al., (2008), *Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data*, ACRP Report 9, U.S. TRB, http://www.trb.org/Publications/Blurbs/Summarizing_and_Interpreting_Aircraft_Gaseous_and_160507.aspx

Whitefield, P., Hagen, D. and Lobo, P. (2009), *Inter-comparisons of PM Emissions from CFM56 Engines Burning Bio-, FT and Conventional Fuels*, Cambridge Particle Meeting, Cambridge, UK, http://www-diva.eng.cam.ac.uk/energy/nickparticle/particle_meeting_09/PWhitefield(MST)_alternative_aviation_fuels.pdf, March 2009

Whitefield, P., Lobo, P., and Hagen, D. (2011), *Aircraft-generated PM Emissions: APU, Tire Smoke and Brake PM Emissions Generated by In-service Commercial Transports and Comparison of PM emissions from Hydro-treated Renewable Jet Fuel (HRJ), and JP8.* Presented at Cambridge Particle Meeting, University of Cambridge, UK, May 13, 2011. Accessed on June 17, 2011 from: http://www.cambustion.com/sites/default/files/instruments/cambridgeparticlemeeting/2011/PWhitefield%26PLobo(Missouri)_2011_Aircraft_PM_Emissions.pdf

Whitefield, (in progress), P. D., *PARTNER Project 37 Non-volatile particulate matter*; Missouri University of Science and Technology

Whyte, R. (1982), *Alternative Jet Engine Fuels*, NATO Advisory Group for Research and Development

ABBREVIATIONS AND ACRONYMS

The following abbreviations and acronyms are defined in this document.

Term	Definition
AAFEX	Alternative Aviation Fuel Experiment
ACRP	Airport Cooperative Research Program
AEDT	Aviation Environmental Design Tool
AERMAP	AERMAP is a terrain preprocessor for AERMOD
AERMET	AERMET is a meteorological data preprocessor for AERMOD
AERMOD	American Meteorological Society/Environmental Protection Agency Regulatory Model
AF	Alternative fuel emission factors ratio
AIR	Aerospace Information Report
APEX	Aircraft Particle Emissions eXperiment
APU	Auxiliary Power Unit
AQEG	Air Quality Expert Group
ARP	Aerospace Recommended Practice
ASTM	American Society for Testing and Materials
ATL	Hartsfield-Jackson Atlanta International Airport
B5	Biodiesel – 5%
B10	Biodiesel – 10%
B15	Biodiesel – 15%
B20	Biodiesel – 20%
B85	Biodiesel – 85%
B100	Pure Biodiesel
BA	British Airways
BOS	Boston Logan International Airport
BTL	Biomass-to-liquids
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAEP	Committee on Aviation Environmental Protection
CHP	Combined Heat and Power
CI	Compression-ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CARB	Californian Air Resources Board
CORINAIR	Core Inventory of Air Emissions
CTL	Coal-to-liquids
DEM	Department of Environmental Management
DEM	Digital Elevation Model
DEN	Denver International Airport
DFW	Dallas Fort Worth International Airport

Term	Definition
DRI	Data Rating Index
DTW	Detroit Metropolitan Airport
E5	Ethanol – 5%
E10	Ethanol – 10%
E15	Ethanol – 15%
E85	Ethanol – 85%
EDMS	Emissions and Dispersion Modeling System
EEA	European Environmental Agency
EfW	Energy from Waste
EGT	Exhaust Gas Temperature
EI	Emission index (typically related to fuel flow and in g/kg fuel)
EI_n	Emission index for non-volatiles
EI_{bc}	Emission index for black carbon
EIS	Environmental Impact Statement
EMEP	European Monitoring and Evaluation Program
EMFAC	Emissions Factors Model
EPA	U.S. Environmental Protection Agency
FAA	Federal Aviation Administration
FAA	Federal Clean Air Act
FAT	Fresno Yosemite International Airport
FOA	First-Order Approximation
FT	Fischer-Tropsch
GA	General aviation
GHG	Greenhouse Gas
GPU	Ground Power Unit
GSE	Ground Support Equipment
GTL	Gas-to-liquids
H_2SO_4	Sulfuric Acid
HC	Hydrocarbon
HDD/CDD	Heating Degree Days/ Cooling Degree Days
HDV	Heavy-Duty Vehicle
HPN	Westchester County Airport
HRJ	Hydroprocessed Renewable Jet Fuel
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILEAV	Inherently Low Emission Airport Vehicle
IEPA	Illinois Environmental Protection Agency
LAS	Las Vegas McCarran International Airport
LAX	Los Angeles International Airport
LDV	Light Duty Vehicle

Term	Definition
LL	Low Lead
LNG	Liquefied Natural Gas
LNK	Lincoln Airport
LPG	Liquefied Petroleum Gas
LTO	Landing and Takeoff
M85	Methanol
MHT	Manchester-Boston Regional Airport
MOBILE	Older U.S. road vehicle emission model (superseded by MOVES)
MOVES	Motor Vehicle Emission Simulator (New U.S. regulatory road vehicle emission model)
MSP	Minneapolis-St. Paul International Airport
NAAQS	National Ambient Air Quality Standards
NAEI	National Atmospheric Emissions Inventory
NCDC	National Climatic Data Center
NEPA	National Environmental Policy Act
NGV	Natural Gas Vehicle
NMVOCs	Non-Methane Volatile Organic Compounds
NO_2	Nitrogen Dioxide
NOx	Oxides of Nitrogen
O_3	Ozone
ORD	Chicago O'Hare International Airport
P	Penetration factor – associated with AF above
PARTNER	Partnership for Air Transportation Noise and Emissions Reduction
Pb	Lead
PHL	Philadelphia International Airport
PHL CEP	Philadelphia International Airport Capacity Enhancement Program
PHX	Phoenix Sky Harbor International Airport
PM	Particulate mater
$PM_{0.1}$	Ultra-fine particulate matter (<0.1 micrometer diameter)
PM_{10}	Coarse particulate matter (<10 micrometer diameter)
$PM_{2.5}$	Fine particulate matter (<2.5 micrometer diameter)
PMvol	Volatile particulate matter
PMsec	Secondary particulate matter
PMnonvol	Non-volatile particulate matter
PN-EI	Particle Number Emission Index
PPC/AEA	Project Performance Corporation/AEA
PSD	Prevention of Significant Deterioration program
PSDH	Project for the Sustainable Development of Heathrow
PVD	Providence TF Green Airport
RIAC	Rhode Island Airport Corporation
SAE	Society of Automotive Engineers

Term	Definition
SAN	San Diego International Airport
SDCRAA	San Diego County Regional Airport Authority
SEA	Seattle-Tacoma International Airport
SIMMOD	Airport and Airspace Simulation Model
SIP	State Implementation Plan
SMF	Sacramento International Airport
SN	Smoke Number
SO_2	Sulfur Dioxide
SO_4	Sulfate
SO_x	Oxides of Sulfur
SPK	Synthetic Paraffinic Kerosene
TAAM	Total Airspace and Airport Modeler
THC	Total Hydrocarbons
TRB	Transportation Research Board
ULS	Ultra-Low-Sulfur Fuel
U.S.G.S.	United States Geological Society
UNECE	United Nations Economic Commission for Europe
VALE	Voluntary Airport Low Emission Program
VMT	Vehicle Miles Traveled
VOC	Volatile Organic Compound

APPENDIX A: LITERATURE REVIEW

This appendix discusses the following:

- Airport sustainability plans, air quality and noise management reports
- Monitoring of fine particulate matter with a diameter of less than 2.5 micrometers (PM2.5) in the vicinity of airports
- Calculation of emissions at airports
- Aircraft and auxiliary power unit (APU) emissions
- Aircraft alternative fuels
- Ground support equipment (GSE) emissions
- GSE alternative fuels
- Road vehicle emissions
- Road vehicle alternative fuels
- Other emission sources
- Dispersion modeling at airports

AIRPORT SUSTAINABILITY PLANS, AIR QUALITY AND NOISE MANAGEMENT REPORTS

In response to airport environmental stewardship initiatives or recent requests from regulatory agencies and the general public, airports are increasingly preparing environmental sustainability plans and air quality management plans on a voluntary basis. These plans generally include air emission inventories, with $PM_{2.5}$ emissions among the pollutants evaluated. Airports may also be driven to assess $PM_{2.5}$ emissions to improve public relations, further sustainability initiatives, cut operational costs or adopt a proactive stance on air pollution. Similarly, noise management reports, sustainability plans and the data collected to support them can also be used as a basis for calculating airport emissions inventories. This is especially the case with the ongoing development of the U.S. Aviation Environmental Design Tool (AEDT) combined noise and air pollution model, which will replace the Federal Aviation Administration's (FAA) Emissions and Dispersion Modeling System (EDMS) in the future.

For example, Boston Logan International Airport prepares an annual environmental data report in which $PM_{2.5}$ emissions are computed for all airport-related sources (e.g., aircraft, APUs, GSE, stationary sources and road vehicles) (Massport, 2008). Under state law, the Rhode Island Airport Corporation (RIAC) also prepares an air emissions inventory for T.F. Green Airport, which includes an annual inventory of greenhouse gases (GHGs) and criteria air pollutants (RIAC, 2009). Similarly, in 2009, the San Diego County Regional Airport Authority (SDCRAA) prepared its first GHG and criteria pollutant emissions inventory for San Diego International Airport (SAN) as part of a memorandum of understanding with the California Attorney General's Office (MOU, 2008).

MONITORING OF $PM_{2.5}$ IN THE VICINITY OF AIRPORTS

Several $PM_{2.5}$ air monitoring campaigns have been carried out at airports across the U.S. (SCAQMD, 2000a, 2000b; Fanning et al., 2007; Westerdahl et al., 2008; Hu et al., 2009; Massport, 2010; ENVIRON, 2008; RI DEM, 2008; Dodson et al., 2009 and BCAA, 2006), with the overarching goals of apportioning airport contributions to $PM_{2.5}$ and assessing the potential impact of $PM_{2.5}$ on nearby residences and public areas. To summarize, the overall findings appear to indicate that while airports may be contributing to emissions, their overall impact (ambient concentration) away from key sources diminishes rapidly and that other key sources such as road vehicles may have more of an impact on local air quality, depending on the relative locations of the sources of the emissions and the location of interest (i.e., ambient monitoring location).

CALCULATION OF EMISSIONS AT AIRPORTS

The following sections outline the methodologies typically used to estimate airport $PM_{2.5}$ emissions, primarily in the U.S. context, but also with reference to other key studies. Each section deals with a particular source sector such as aircraft, APU, GSE, roadways, parking lots, and other ancillary sources such as stationary sources. In addition, each section also discusses methodologies relevant to the estimation of airport-related $PM_{2.5}$ from alternative fuels.

AIRCRAFT AND APU EMISSIONS

An aircraft's engine is its main propulsion unit and comes in four main types—turbofan, jet turbine, turboprop (including turboshaft), and piston.

- Turbofan engines combine a gas turbine with a ducted fan and are primarily used on executive jets and larger, high-altitude passenger aircraft. They burn aviation kerosene, known as Jet-A in the U.S.
- Jet turbine engines are similar to turbofans, but do not have a fan. They also burn Jet-A.
- Turboprop engines combine a gas turbine with a propeller and are primarily used on short-range, medium-altitude executive aircraft, airliners, and helicopters. This kind of engine primarily burns Jet-A.
- Piston-engines are reciprocating internal combustion engines used to power small, short-range, low-altitude general aviation aircraft. This kind of aircraft engine primarily burns leaded aviation fuel called AvGas. The most common grade is 100LL (low lead).

APUs are small gas turbines that typically burn Jet-A. They are usually mounted at the rear of larger executive aircraft and airliners. These units supply electricity to operate electrical, hydraulic and air-conditioning systems when the main aircraft engines are not running. APUs are also used for main engine startup.

The majority of aircraft use turbine technology and burn Jet-A (or similar) fuel. Whitefield et al. (2008) provides the following typical diameters of types of particulate matter emitted from aircraft turbine engines:

- Non-volatile carbonaceous particulate matter (soot or black carbon) ranging from 0.02 μm to 0.06 μm
- Volatile particulate matter ranging from 0.001 μm to 0.015 μm

Both of these types of particulate matter are typically classified as PM_{10}, $PM_{2.5}$, and $PM_{0.1}$.

Jet Turbines and Turbofans

The development of methods to estimate the emissions of particulate matter from aircraft engines is still at a relatively early stage when compared with other modes of transport. It relies primarily on the International Civil Aviation Organization (ICAO) regulatory compliance measurement of smoke emissions from aircraft engines for engine certification. Similar certification data are also available for hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emission rates. Smoke number (SN) measurement is an imprecise, 50-year-old method that does not provide any data on particle size, type or size distribution and does not represent all of the particulate matter that have an impact on human health and the environment. Furthermore, the smallest particulate matter found in aircraft engine exhausts can penetrate the smoke filter used to measure SN, so the SN is more likely to be representative of larger smoke particles.

Therefore, the ICAO’s Committee on Aviation Environmental Protection (CAEP) tasked the Society of Automotive Engineers’ (SAE) E-31 Aircraft Exhaust Emissions Measurement Committee (which comprises research institutes, engine manufacturers, and regulators) with developing a methodology.

In April 2002, the E-31 Committee issued a position paper (SAE, 2004) calling for the development of a set of aircraft engine particulate matter measurement recommendations covering:

- Measurement at the engine exit
- Characterization of non-volatile particulate matter
- Exclusion of the characterization of volatile particulate matter

In April 2003, this led to the publication of *Aerospace Information Report (AIR) 5892, Nonvolatile Exhaust Particle Measurement Techniques*, with AIR 5892 Revision A following in July 2004 (SAE, 2004). Over the past decade, a series of research projects in Europe and the U.S., including PartEmis (Petzold et al., 2005), Aircraft Particle Emissions eXperiment (APEX) (Kinsey, 2009) and SAMPLE (Petzold et al., 2009), have been completed, with additional testing in progress (e.g., SAMPLE II (European Aviation Safety Agency, 2009)).

These experiments have helped to gain a better understanding of emissions at the engine exit plane and in the exhaust plume. This work has also been used to evaluate existing estimation methodologies.

Also in 2003, a literature review of particulate matter estimation methodologies was conducted (Wasyon et al., 2003), leading to the development of the current particulate matter estimation methodology, the first-order approximation (FOA), based on the three most widely recognized studies at the time (Champagne, 1971; Whyte, 1982; Hurley, 1993). The FOA has evolved over time, with the current international version, FOA3, developed by the ICAO’s CAEP (ICAO 2007 and 2011). FOA3 is applicable to certified commercial aircraft engines above 26.7 kN of thrust. The current U.S. version is FOA3a, which is incorporated in the U.S. regulatory model for airport air quality, EDMS (U.S. FAA, 2009). EDMS assumes that all PM_{10} is $PM_{2.5}$ and uses FOA3a only when appropriate SN data are present.

The general consensus is that the FOA methodology is not sufficiently accurate and that work in the U.S. (including the U.S. Environmental Protection Agency (EPA), FAA, Volpe, and SAE E-31 Committee) and Europe is ongoing to improve it (Volpe, 2010). Ultimately, it is intended that the FOA methodology will be replaced by a database of verified engine emissions with an aerospace recommended practice (ARP) for aircraft non-volatile particulate matter issued. This is expected to happen by December 2011 (Whitefield, in progress).

FOA3a

FOA3 was completed in late 2006. It was accepted in February 2007 for international use by CAEP and first published in the Airport Air Quality Guidance Manual (ICAO, 2007) and subsequently in 2011 (ICAO, 2011). It has been supplemented by FOA3a in the U.S. However, both methodologies are in use and have been incorporated into EDMS, with U.S. airports using the EPA's approved FOA3a and non-U.S. airports using the ICAO/CAEP approved FOA3 (CSSI, Inc., 2009).

The FOA3 methodology, including assumptions and derived equations, is discussed in detail in the publication *Methodology to Estimate Particulate Matter Emissions from Certified Commercial Aircraft Engines* (Wayson et al., 2009). FOA3a builds on the FOA3 methodology and was developed under *PARTNER Project 15 Aircraft Impacts on U.S. Local and Regional Air Quality* (Ratliff et al., 2009). It was completed in 2009.

To summarize, the total particulate matter emissions from an engine are calculated by summing the volatile and non-volatile contributions:

$$PM_{total} = PM_{vol} + PM_{nvol}$$

The methodology also identifies the three main components of volatile particulate matter in aircraft engine exhausts as:

$$PM_{vols} = F(\text{fuel sulfur content}) + F(\text{fuel organics}) + F(\text{lubrication oil organics})$$

Based on the limited data available at the time, volatile particulate matter driven by nitrates was considered to be a small contributor to the total particulate matter and, as the residency time is short, they were not incorporated into the FOA3 methodology.

Non-volatile Contribution to Particulate Matter

The link between non-volatile particulate matter emissions and SN is well established and the FOA3 and FOA3a (Wayson et al., 2009; Ratliff et al., 2009) methodologies reflect this by deriving estimates for PM_{nvol} from the SNs listed in the ICAO Engine Emissions DataBank (2010). In the non-volatile component, FOA3 and FOA3a allow for instances when the SN is measured with bypass air (the air that passes through the engine, but does not pass through the engine core). The engine bypass ratio, β, is used as a multiplier, in the form $(1 + \beta)$, to estimate the exhaust volume.

In FOA3a, this approach is applied to all aircraft engines (Wayson et al., 2009; Ratliff et al., 2009), but it is strictly only a suitable assumption for engines where the core flow and bypass flow are mixed before the engine exit plane. The majority of aircraft engines flying today mix the flows after the exit plane. In engines with external mix, this multiplication factor is conservative as it increases the non-volatile primary particulate matter component.

Fuel Sulfur Content Contribution to PM_{vol}

The quantity of sulfates produced in an engine exhaust is directly linked to the sulfur content of the fuel. Under ASTM International's D1655 specification, aviation fuel (Jet-A) can contain up to 0.3% sulfur by mass (ASTM, 2010). Typically, the sulfur content in aviation fuel is considerably lower than this (as low as 0.05% (ICAO, 2007 and 2011)).

FOA3a assumes a conservative fuel sulfur content of 0.068% by mass (the value listed in the American Gasolineeum Institute's Handbook of Aviation Fuel Properties) and a sulfur dioxide (SO_2) to sulfuric acid (H_2SO_4) conversion efficiency factor of 5%.

Organic Contribution to PM_{vol}

Organic particulate matter comes about as a result of incompletely combusted fuel and species formed through pyrolysis in the engine's combustion chamber. As with fuel sulfur content contributions, residence time and atmospheric conditions are important determinants of the organic contribution.

Data gathered from testing a single CFM56-2-C1 engine during the Aircraft Particulate Emissions eXperiment (APEX) 1 were used to inform the calculation of the organic contribution to particulate matter.

Two key assumptions regarding the APEX 1 results were made to permit the estimation of fuel organic particulate matter emissions for all engines. The first is that the test data gathered from one engine are representative of all engines in the ICAO Engine Emissions DataBank (2010). The second is that fuel organic particulate matter is proportional to total HC emission indexes, which are measured to achieve engine certification.

Lubrication Oil Contribution to PM_{vol}

A development of FOA3a over FOA3 included an estimate for the contribution of engine lubrication oil to particulate matter emissions. Data were scarce at the time, so engineering judgments were made based on engine manufacturer data.

The conclusion was that around 1.4 grams (Wayson et al., 2009; Ratliff et al., 2009) of volatile organic particulate matter is released per landing and takeoff (LTO) cycle, and this was added to the contribution from fuel organics to arrive at a total organic volatile component.

Turboprop and Turboshaft Aircraft

EDMS includes emission factors for turboprop and turboshaft aircraft for some pollutants, but it does not include emission factors related to particulate matter, as there are no FAA accepted emission factors for these aircraft. Very little data exist on turboprop and turboshaft aircraft particulate matter emissions. For the ACRP 02-23 project, two key sources of particulate matter emission factors were reviewed for suitable data with regard to turboprop and turboshaft aircraft, one from the U.S. Air Force (2002) and a supplement to the EPA AP-42 (U.S. EPA, 1980). It should be noted that these data relate to particulate matter in general and not to $PM_{2.5}$, though it has been assumed that all particulate matter is $PM_{2.5}$. In addition, military aircraft may not be using Jet-A specification fuel, but will be using a similar military specification (e.g., JP-8).

Piston-engine Aircraft

EDMS includes emission factors for piston-engine aircraft for some pollutants, but there is no inclusion of particulate matter from piston-engine aircraft (ACRP, 2008). In general, data on particulate matter emissions from piston-engine aircraft are scarce. However, the Swiss have undertaken a test program to measured CO, HC and NOx for 17 piston-engine aircraft. Particulate matter emissions were also measured in a parallel project that looked at the impact of using different fuels and additives on particulate matter emissions (FOCA, 2007a). The Swiss study suggests the soot emission factors shown in Table 8 (all in the 2.5 micron range), with 91/96UL being the best alternative fuel from a particulate matter perspective.

Table 8 – Soot Emission Indices (mg/kg fuel)

Fuel	Taxi	Approach	Climb	Takeoff
AvGas 100LL (leaded)	50	40	70	100
AvGas 91/96UL (unleaded)	1	1	2	3

Source: FOCA, 2007a.

Auxiliary Power Unit Particulate Matter Emissions Estimation

The EDMS database contains emission factors for PM_{10} and $PM_{2.5}$ for APUs. The emission factors used in EDMS were sourced from FAA and EPA documentation and industry correspondence. The FAA reviewed the information available in 2000 by getting the principal manufacturer (Honeywell) to comment on the datasets the FAA was recommending at the time. The resulting set of APU emission indices have been widely used in compiling airport emissions inventories.

ICAO's Airport Quality Guidance Manual (ICAO, 2007 and 2011) outlines three APU estimation methodologies that focus on NOx, HC, CO and PM_{10} emissions – a simple approach, an advanced approach and a sophisticated approach. Each of these requires an increasing resolution of data and offers an increasing level of accuracy of output. The simple approach would appear to be similar to that used in EDMS. The advanced approach, in principle, is based on work for the Project for the Sustainable Development of Heathrow (PSDH) study, where British Airways (BA) derived data from detailed manufacturer's data (Underwood, 2007). The sophisticated approach is only appropriate where very detailed data can be obtained.

The Airport Cooperative Research Program (ACRP) Project 02-06 report (Webb et al., 2008) discusses potential needed research in the context of airports and particulate matter. From that report, there is a recently commissioned study (Missouri University of Science and Technology, in progress) that should provide a better basis for data on APU emissions and that could be incorporated into EDMS in the future. Ideally, the ACRP 02-23 project would have incorporated that data. However, that was not feasible due to timescales, but it is recommended that it be included in future studies.

Brake and Tire Wear

No brake and tire wear is included in EDMS for aircraft or, typically, in U.S. airport emissions inventories in general. However, estimates of brake and tire wear for a number of airport emissions inventories, since and prior to the PSDH study (Underwood, 2007), have been included for UK airports.

Without undertaking aircraft specific calculations outside EDMS, and given that brake and tire wear emissions are not directly affected by the use of alternative fuels, these have not been considered further in the ACRP 02-23 project.

AIRCRAFT AND APU ALTERNATIVE FUELS

Most of the research on alternative fuel emissions for aircraft has been related to jet fuel, which is used in turbine powered aircraft. As discussed previously, there is relatively little information available in the context of $PM_{2.5}$ emissions for piston-engine aircraft fueled by AvGas or diesel. In addition, the majority of aviation fuel consumed in the U.S. is jet fuel as opposed to AvGas. As of July 2011, the average petroleum products supplied, per day, in the U.S. are: aviation gasoline 15 thousand barrels; and kerosene-type jet fuel 1418 thousand barrels (U.S. Energy Information Administration, 2011). Therefore, the ACRP 02-23 project has concentrated on jet fuel alternatives.

The high capital cost of airport infrastructure, distribution systems, and replacement of engines and supporting aircraft systems makes drop-in fuels economically necessary. To assure quick and widespread adoption of an alternative to jet fuel, the commercial airlines and the military require that the fuel be a drop-in fuel. The primary domestic fuel currently used in commercial aircraft turbine engines is a petroleum-derived Jet-A (ASTM D1655). Jet A-1 is the international standard for commercial jet fuel and JP-8 is the U.S. military's jet fuel; both are derived from petroleum.

According to the Commercial Aviation Alternative Fuels Initiative's (CAAFI) website glossary (CAAFI, 2010), a drop-in fuel:

- May be used "as-is" on existing aircraft.
- "Is completely interchangeable and compatible with conventional jet fuel when blended with conventional jet fuel".
- Requires no changes to the aviation fuel distribution system or aircraft or engine fuel system.

There are many types of feedstock being considered for use as a substitute for jet fuel. The feedstocks must be able to produce a sufficient quantity to satisfy the growing demand for aviation fuel, estimated in 2011 as 14 million barrels per day for jet fuel and 14 thousand barrels per day for aviation gasoline in the U.S. (U.S. Energy Information Administration, 2011). To be adopted, the jet fuel developed must meet all of the specifications of jet fuel standards (e.g., freezing point, viscosity, flash point, density, and sulfur content). The International Air Transport Association's (IATA) Fact Sheet on Alternative Fuels summarizes the requirements of jet fuel as having a freezing point below -40^oC for Jet-A and -47^oC for Jet A-1, not forming deposits in the engine in high-temperature locations and having an energy content of at least 42.8 MJ/kg (IATA, 2010). The two major categories of alternative jet fuels are alternative fossil fuels and biomass fuels. Newer alternative fuels are frequently referred to by their source feedstock (coal, natural gas, or a specific plant or animal biomass) and their chemical processing methods, such as Fischer-Tropsch (FT) or hydroprocessed renewable jet (HRJ). Examples of alternative jet fuels derived from fossil fuels include natural gas (gas-to-liquid (GTL)) and coal (coal-to-liquid (CTL)). Examples of biomass-to-liquid (BTL) fuels include those derived from animal fats or from plants such as sorghum, switchgrass, jatropha, algae, and camelina.

In 2011, the ASTM D7566 – 11a *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons* was approved. This standard "covers the manufacture of aviation turbine fuel that consists of conventional and synthetic blending components" (ASTM, 2011). "Aviation turbine fuel manufactured, certified and released to all the requirements of this specification, meets the requirements of Specification D1655 and shall be regarded as Specification D1655 turbine fuel", (ASTM, 2011). As a result of this newest revision of ASTM D7566, alternative fuels from both FT (BTL, CTL, GTL) and HRJ (described as Hydroprocessed Esters and Fatty Acids (HEFA) fuel derived from biomass feedstocks) produced according to D7566 are to be regarded as D1655 turbine fuels.

Careful attention is necessary when attempting to compare results of studies when different percentages of full throttle are used or different engine power setting referencing methods are used (such as percent thrust, percent maximum continuous power or other engine parameters). Engine thrust settings influence emissions, particle size and chemical composition. Therefore, it is assumed in the ACRP 02-23 project that the AAFEX results have been normalized to negate the effects of temperature and pressure changes. The ICAO LTO default specifies thrust setting as a percentage of full throttle and the duration in minutes. EDMS uses the following default thrust settings, though the timing may be altered by the user:

- 7% for 26 minutes, representing idle
- 100% for 0.7 minutes, representing takeoff
- 85% for 2.2 minutes, representing climb-out
- 30% for 4.0 minutes, representing approach

The three categories of alternative fuel types explored fully in the RAND 2009 (Hileman et al., 2009) report are:

- Production from oil sands and oil shale
- Fischer-Tropsch (FT) synthesis of natural gas, coal, and biomass
- Refining oil products from biomass into synthetic paraffinic kerosene (SPK) fuel

HRJ and FT fuels have a similar chemical structure. The emissions of particulate matter and secondary particulate matter from sulfur are expected to be reduced by more than 10% compared with the baseline fuel (Jet-A) according to the RAND 2009 report. Similarly, using camelina HRJ as a drop-in fuel could reduce carbon dioxide (CO_2) emissions by over 80% during the life-cycle from the field to the wake (Goodrich, 2009). Ultra-low-sulfur jet fuel (ULS) is suggested in the RAND 2009 as a more quickly realizable method to reduce primary and secondary particulate matter caused by aviation. "ULS conventional" is jet fuel produced with lower acceptable sulfur levels (i.e., between 10 and 100 ppm).

Large reductions in particulate matter emissions are possible using FT fuels (Hileman et al., 2009). As the percentage of FT fuel increases, the reduction in particulate matter mass also increases, as found in U.S. Air Force tests comparing jet fuel with varying percentages of FT fuel. Recent tests in the Alternative Aviation Fuel Experiment (AAFEX) program were designed to run combinations of FT (two separate fuels, GTL and CTL), biomass fuels, and Jet-A in a CFM56 (a modern, high-bypass turbofan engine) operating on the ground on a DC-8 (Whitefield et al., 2008). Using low-sulfur, low-aromatic alternative fuels, such as those created from FT synthesis, may reduce primary particulate matter and appears to provide consistent particulate matter reductions across a variety of types and ages of gas turbine engines (Hileman, 2008).

Military JP-8 and FT fuels tests on turboshaft engines, similar to turboprop engines, revealed that total particulate matter carbon, or non-volatile, emissions and diameters increased with increased engine power settings at idle, 75% of maximum continuous and 100% of maximum continuous power (Cheng et al., 2008). The engines were T700 and T701C GE engines, typically used in helicopters. Neat FT fuel (not blended with any other fuel) had reduced elemental carbon emissions, attributed to the lack of aromatics, which are soot precursors. Neat FT fuel had reduced organic carbon emissions at idle power, but not at higher engine power settings. Formation of volatile particulate matter emissions is negligible in neat FT fuel due to the lack of aromatics and sulfur. Tests show that elemental carbon (soot) emissions for engines running FT and JP-8 were dramatically higher at maximum continuous power than other power settings—130 g/m^3 and 30 g/m^3, respectively. For the FT fuel, elemental carbon at idle (not specified further) and 75% of maximum continuous power was negligible. Organic carbon (non-soot) emissions for the JP-8 and FT engines were reported as statistically identical.

Particulate matter mass emission indices ranged from 0.2 to 1.4 g/kg fuel for the T700 and 0.2 to 0.6 g/kg fuel for the T701C (Corporan and Cheng, 2010). The entire fleet of U.S. Air Force (USAF) aircraft is expected to be certified to use blended alternative fuels by 2016. The U.S. Air Force is currently certifying aircraft to operate with a 50/50 blend by volume of FT and JP-8 fuel. The emissions of the T701C engine were compared while using JP-8 fuel and a neat FT fuel (Syntroleum Corporation's GTL from natural gas). FT fuels have smaller particle number emission indices (EI) relative to fuel flow at all power settings (less than 1.0×10^{14} at idle) compared to convention fuel, typically, with reductions of between 40% and 97% in particle number emission indices (PN-EI) and the highest reductions at idle. Particle size distributions for FT are dramatic, with average reductions of 25% in mean particle diameter observed at all power settings. Smoke numbers for FT fuel at the three power settings were dramatically lower – an average of 65%. Smoke number (SN) trends are consistent with PN-EI trends. All engines produced higher CO and lower NO_x emissions at the lower power settings. NO_x emissions for FT were negligibly different. CO emissions were reduced by between 5% and 10% using FT. Formaldehyde (HCHO) is the primary aldehyde produced and FT fuel had minimal impact on production, except at the 75% of maximum continuous power setting.

AAFEX was conducted in 2009 at NASA's aircraft facility in Palmdale, California in the Dryden Flight Research Center DC-8. NASA acquired and burned JP-8, FT GTL (FT-1) and FT CTL (FT-2) fuels to assess changes in performance and emissions in the two inboard CFM-56 main engines (AAFEX, 2010). The key results, in the context of the ACRP 02-23 project, are shown in Table 9.

In addition to the studies on the CFM-56 main engines, AAFEX also reported the effects of alternative fuels on the APU. The Garrett AiResearch GTCP85-98 CK APU onboard a DC-8 parked at Palmdale, California, was studied in January and February 2009 (Beyersdorf and

Anderson, 2009) using two fuels – JP-8 and FT CTL. Running JP-8, the black carbon and organic compound emissions from the APU were measured as exhaust gas temperature (EGT) increased. As EGT increased from around 365°C to 610°C, the emissions dropped for black carbon and organic compounds. Using approximations from Beyersdorf and Anderson (2009), the black carbon emissions at around 365°C were nearly 500 mg/kg of fuel burned, and at around 610°C were around 200 mg/kg of fuel burned. APU emissions were reported as around 20 times the emissions from the DC-8's CFM56 engine at idle. Using approximations from the study, the organic compound emissions at around 365°C were between 6 and 7 mg/kg of fuel burned, and at around 610°C were around 200 mg/kg fuel burned.

Running FT CTL in the same AAFEX study, the black carbon and organic compound emissions from the APU were measured as EGT increased. As the EGT increased from around 365°C to 610°C, emissions dropped for black carbon and organic compounds. Using approximations from the study, the black carbon emissions at around 365°C were about 40 mg/kg of fuel burned and at around 610°C were about 5 mg/kg of fuel burned. Using approximations, from Figure 5 in the AAFEX study, the organic compound emissions at around 365°C were about 1 mg/kg of fuel burned and at around 610°C were about 0.5 mg/kg of fuel burned. Analysis of data from AAFEX II experiments using HRJ fuels is underway, and readers should consider those results when they become available.

The Partnership for Air Transportation Noise and Emissions Reduction (PARTNER) is an FAA Center of Excellence, sponsored by the FAA, NASA, Transport Canada, the U.S. Department of Defense and the EPA. PARTNER Project 20, *Emissions Characteristics of Alternative Aviation Fuels* (Missouri University of Science and Technology, 2011a), is working with the aviation community to gather accurate data on emissions from candidate alternative fuels and to compare these emission characteristics with those of conventional aviation fuel types being gathered in PARTNER Project 9, *Measurement of Emissions* (Missouri University of Science and Technology, 2011b). These data will provide the essential information for PARTNER Project 17, *Alternative Fuels* (Missouri University of Science and Technology, 2011c) and to the aviation community at large as it charts a course for environmental sustainability in an uncertain energy future. The planned outcome is the creation of a database of particulate matter and hazardous air pollutant emissions from engines burning Jet-A/JP-8 and alternative fuels, such as FT synthetic fuel.

The data found from the literature review have been used to generate emission factors for alternative fuels as summarized in Table 9.

Table 9 – Data to Support Alternative Aircraft Fuel Emission Factors

Turbine Engine	Fuel Type	Engine Setting	SO_x (mg/kg fuel)	SN	EI particles/kg fuel	Black Carbon mg/kg fuel	HC EI g/kg fuel	Source
T-63	**FT GTL blended with JP-8 (0% up to 100% FT)**	Idle. 0.40 kg/minute fuel flow	Decrease linearly with increase in FT%	0-100% FT 6.6 to <1				Corporan et al., 2007

Turbine Engine	Fuel Type	Engine Setting	SO_x (mg/kg fuel)	SN	EI particles/kg fuel	Black Carbon mg/kg fuel	HC EI g/kg fuel	Source
		Cruise. 1.32kg/minute fuel flow	Decrease linearly with increase in FT%	0-100% FT 29.7 to 3.8				Corporan et al., 2007
	FT GTL 50/50 blend with JP-8	Low		PM EI 0.53 of JP-8				Corporan et al., 2007
		High		PM EI 0.46 of JP-8				Corporan et al., 2007
	JP-8 and Methyl Ester Biofuel Blend (80/20)	Ground idle		7.5				Corporan et al., 2007
		Cruise		31.4				Corporan et al., 2007
		Takeoff		35.3				Corporan et al., 2007
T700-GE-701C	**FT GTL**	Idle		65% reduction using FT over JP-8 on same engine. Negl.				Corporan and Cheng 2010
		75% MCP		2				Corporan and Cheng 2010
		100% MCP		12				Corporan and Cheng 2010
CFM56	**FT GTL neat**	Low power (4%-45% max rated power) [4% 1,000 lbs/hour]	<0.3		0.1 JP-8 (90% reduction compared with JP-8)			Beyersdorf and Anderson, 2009
		7% max rated thrust				0.41 JP-8		Anderson et al., 2011
		85% max rated thrust		0.16 JP-8		0.41 JP-8		Anderson et al., 2011
		85% max rated thrust	<0.3					Miake-Lye et al., 2009
		High					1	Bulzan et al., 2010
		100% max rated thrust [7,600 lbs/hour]	<0.3		0.4 JP-8			Beyersdorf and Anderson, 2009

Turbine Engine	Fuel Type	Engine Setting	SO$_x$ (mg/kg fuel)	SN	EI particles/kg fuel	Black Carbon mg/kg fuel	HC EI g/kg fuel	Source
	FT CTL neat	Low power (4%-45% max rated power) [4% 1,000 lbs/hour]	<0.3		0.1 JP-8			Beyersdorf and Anderson, 2009
		7% max rated thrust				0.53 JP-8		Anderson et al., 2011
		85% max rated thrust		0.29 JP-8		0.59 JP-8		Anderson et al., 2011
		85% max rated thrust	<0.3					Miake-Lye et al., 2009
		High					1	Bulzan et al., 2010
		100% max rated thrust [7,600 lbs/hour]	<0.3		0.4 JP-8			Beyersdorf and Anderson, 2009
	50/50 JP-8/FT GTL	Low power (4%-45% max rated power) [4% 1,000 lbs/hour]			0.5 JP-8			Beyersdorf and Anderson, 2009
		100% max rated thrust [7,600 lbs/hour]			0.7 JP-8			Beyersdorf and Anderson, 2009
	50/50 JP-8/FT CTL	Low power (4%-45% max rated power) [4% 1,000 lbs/hour]	<0.5		0.5 JP-8			Beyersdorf and Anderson, 2009
		100% max rated thrust [7,600 lbs/hour]			0.7 JP-8			Beyersdorf and Anderson, 2009
	All fuels in test							Beyersdorf and Anderson, 2009
Garrett APU GTCP85-98CK	**JP-8**					200-500		Beyersdorf and Anderson, 2009
	100% FT/JP-8 CTL	Low power		0.16 JP-8		0.16 JP-8		Anderson et al., 2011
	100% FT/JP-8 CTL	High power		0.13 JP-8		0.11 JP-8		Anderson et al., 2011
	50/50 JP-8/FT CTL					10-50		Beyersdorf and Anderson, 2009

GROUND SUPPORT EQUIPMENT (GSE) EMISSIONS

GSE emissions tend to refer to the airside emissions from aircraft support equipment, such as mobile generators, air-conditioning units, baggage, fuel, food and cargo trucks, and loaders and tugs. It can also be used to refer to buses used airside to transport passengers between remote aircraft and terminals and cargo trucks. Road vehicles are dealt with separately under road vehicles, and only GSE are discussed further in this section, although there are many parallels with road vehicles.

Conventional Fuels

U.S. federal standards for off-road diesel engines have evolved over a period of time (Dieselnet, 2010). Tier 1 standards were phased in from 1996 to 2000, Tier 2 and Tier 3 standards were phased in from 2000 to 2008, Tier 3 standards for particulate matter were never adopted and Tier 4 standards are to be phased in from 2008 to 2015. The Tier 4 standards require control technologies that include advanced exhaust gas after-treatment.

In addition, nonroad diesel will need to have lower sulfur content in the future. Fuel refiners began to produce low-sulfur nonroad diesel in June 2007 (U.S. EPA, 2009a). This will be further lowered in the future (U.S. EPA, 2004a), which should reduce the particulate matter emissions, as sulfur acts as a substrate for secondary particulate matter formation.

In the U.S., emissions for GSE are typically calculated using the inbuilt EDMS model emission factors (refer to the section Conventional Fuels under Road Vehicle Emissions for trucks and buses). The emission factors were generated in EPA’s NONROAD2005 emission factor model in EDMS version 5.1.2 (U.S. FAA, 2009) because the engines used by GSE manufacturers are those typically used elsewhere in other equipment (due to market size). A more recent version of the NONROAD model is available (U.S. EPA, 2008). The NONROAD model for off-road vehicles covers compressed natural gas (CNG), liquefied petroleum gas (LPG), 2- and 4-stroke gasoline, and diesel fuel. Internally, NONROAD develops this information based on available engine testing data, such as from certification.

The NONROAD emission factors are only available for total $PM_{2.5}$ for GSE within EDMS. However, the derived emission factors incorporate deterioration factors. The emission factors derived from NONROAD $PM_{2.5}$ also incorporate some volatile emissions (i.e., from sulfur) (U.S. EPA, 2005). However, other volatile emissions from other pollutant interactions are not specifically included (although some will be accounted for as primary exhaust emissions are based on certification data). Similarly, brake and tire wear or re-suspended solids, such as dust, are not included. Ideally, these sources would be included in this ACRP 02-23 project; however, developing the EDMS model and detailed emission factors for these sources is beyond the scope of the ACRP 02-23 project other than in the context of alternative fuels.

The ICAO/CAEP guidance (ICAO, 2007 and 2011) suggests two simplified approaches, based on aircraft movements (multiplied by an appropriate average GSE emission factor) or total fuel use and an average GSE emission factor. The more advanced methodology that relates to the PSDH developments in that emissions are calculated on a time-use basis for each piece of GSE and includes degradation and a load factor. The ICAO/CAEP guidance only discusses direct GSE emissions and does not include discussion of brake and tire wear, re-suspension or secondary emissions in the context of GSE. Comparison of the application of a very similar methodology (the same, but without the degradation factor) for GSE and ground power unit (GPU) emissions can be found in the reports from Zurich Airport (Unique, 2004 and 2006).

The ACRP Project 02-06 Report *Research Needs Associated with Particulate Emissions at Airports* (Webb et al., 2008), discussed potential needed research in the context of airports and particulate matter. As a result of this report, there is a recently commissioned study (CDM, in progress) where one of the aims is to develop a “representative inventory of powered GSE at airports to help the industry assess the contribution of GSE to air quality impacts at airports.” Unfortunately, given the ACRP 02-23 project’s timescale, the related data and information could not be used to supplement this study.

It may be feasible for airports in general to obtain estimates of total airside fuel use for a particular airport, which could be used as a mechanism to check estimates of GSE fuel use and, therefore, indicate the validity of the emissions.

Brake and Tire Wear

Ideally, brake and tire wear would be included in the ACRP 02-23 project, although most airport studies in the world do not include brake and tire wear as there is not a defined methodology. However, a recent study for London Heathrow Airport to compile an emissions inventory for a base year of 2008/09 (Underwood et al., 2010) included estimates for brake dust, tire wear and re-suspended road dusts for GSE based on the UK methodology for road vehicles (described in this document under road vehicles). For GSE, it was assumed that the equivalent emissions in terms of g/kg fuel can be applied to small GSE as for cars, medium GSE as medium road vehicles and large GSE as large road vehicles. However, as discussed in the Brake and Tire Wear section under Aircraft and APU emissions of this document, the ACRP 02-23 project is concerned with the impact of alternative fuels, which is not directly affected by brake and tire wear emissions.

GSE ALTERNATIVE FUELS

The Voluntary Airport Low Emission (VALE) program (U.S. FAA, 2010a) is focused on helping airports to improve air quality. It provides funding from the FAA to commercial airports in areas where air quality standards are currently not attainable. In terms of the VALE process, via designated Department of Energy (DOE) and EPA guidelines, eligible alternative fuels are:

- Electricity (including photovoltaic)
- Natural gas and liquid fuels domestically produced from natural gas (CNG or liquefied natural gas (LNG))
- LPG/propane
- Mixtures containing 85% or more by volume of alcohol fuel with gasoline, including denatured ethanol (E85) and methanol (M85) (i.e., biogas)
- Hydrogen
- Coal-derived liquid fuels
- Biodiesel (B85 to B100)
- P-series fuels

Many of these fuels have very limited availability or are still at the research and development stage (e.g., P-series and hydrogen). In terms of air quality emissions, hydrogen and electricity produce zero particulate matter direct emissions.

Examples of the types of electric vehicles and equipment tried at airports include St Paul's Airport, Minneapolis (Energy Efficiency News, 2009); London's Heathrow Airport (Smith Electric Vehicles, 2010); Tokyo's Haneda Airport (TreeHugger, 2008); and many others (U.S. FAA, 2006b and 2010b).

In EDMS, GSE emission factors are available for several fuels (diesel, gasoline, electric, CNG, and LPG) (U.S. FAA, 2009). The CNG and LPG EDMS emission factors appear to be based on an EPA study, which found that particulate matter emissions from 4-stroke, spark-ignition engines running on LPG and CNG were 0.05 g/hp-hour (U.S. EPA, 2004b).

The Inherently Low Emission Airport Vehicle (ILEAV) program (U.S. FAA, 2006b), VALE's predecessor, also looked at non-electric alternative fuels replacements. Although two key alternative fuels reported in the ILEAV program, CNG and LPG, are a replacement for gasoline, because the engines provide a spark, these fuels are not a replacement for diesel fuel in compression-ignition (CI) engines. An engine can be adapted to use these fuels, but it involves major engineering work to change the compression ratio of the engine and add an ignition system. CNG and LPG can be used in a dual-fuel engine, together with diesel; the diesel is needed to ignite the air-fuel mixture in a CI engine.

In terms of other alternative fuels, many existing diesel GSE could theoretically be run using low-sulfur diesel and biodiesel blends without specialist (non-standard) engines designed to run on specific alternative fuels. Biodiesel typically has lower sulfur and aromatic content than standard diesel, which, therefore, generally acts to reduce particulate matter emissions. However, there is a limit to what can be achieved. Most engines are not designed for use with biofuels, especially GSE, where there is a limited market, and many manufacturers will not guarantee existing equipment on higher-biofuel blends. In addition, biofuels are typically thought to improve particulate matter emissions (e.g., compared with diesel) (Lapuerta et al., 2005; Krahl et al., 2009). However, some sources suggest an increase of particulate matter for biodiesel relative to standard diesel (Gaffney and Marley, 2009), although this would appear to contradict the general consensus, and it seems to be related to the hydrocarbon content of the fuel. Further research is needed to quantify the impact that specific types of biofuel (by feedstock, blend and engine type) will have on primary and volatile (i.e., "secondary") particulate matter emissions. In terms of biofuels, it is also worth considering that many will solidify at cool temperatures, block fuel filters and generally create the need for higher maintenance. Similarly, high humidity can cause microbial growth in biofuels, again resulting in higher levels of maintenance.

In terms of low-sulfur diesel, nonroad diesel will need to have lower sulfur content in the future. Fuel refiners began to produce low-sulfur nonroad diesel in June 2007 (U.S. EPA, 2009a). This will be reduced further in the future (U.S. EPA, 2004a), which should act to reduce the particulate matter emissions. Resulting from this, there is a briefing document that accompanies the NONROAD model that suggests sulfur contents to use for future years, will reduce from 2,284 ppm to 11 ppm by 2015 (U.S. EPA, 2009d).

Interestingly, EDMS automatically assumes lower sulfur content when calculating future GSE emissions for SOx, but not other pollutants (U.S. FAA, 2009). It is feasible that the sulfur content can be altered and that an additional set of low-sulfur diesel emission factors can be generated for use in EDMS using the equations within NONROAD's supporting documentation (U.S. EPA, 2010e). This methodology is basically the same in the 2005 version of NONROAD supporting documentation (U.S. EPA, 2004b). However, specific emission factors for E85, M85, B85 and B100 are more difficult to estimate, though Table 3 under Road Vehicle Emissions in Chapter 2 gives some broad factors that could be used to convert emission factors from either gasoline or diesel to bioethanol or biodiesel.

While retrofit technology is not the subject of this report, it could be advantageous to fit equipment (e.g., particulate matter traps) to existing GSE diesel engines given the uncertainties of particulate matter emissions and to be cost-effective. Where vehicle replacement is an option, electric GSE is better when compared with other alternative fuels in terms of reducing directly emitted particulate matter (U.S. FAA, 2010a). Around the world, electric vehicles are available as replacements for baggage tugs and belt loaders. A few other specialist airside electric vehicles have been trialed, and there are a few makes of electric aircraft push-back tugs. However, their relatively modest capacity suggests they would not be very flexible and unable to deal with larger aircraft.

ROAD VEHICLE EMISSIONS

Conventional Fuels

A detailed study by the EPA found that emissions of particulate matter deteriorate exponentially with the age of the vehicle, but remain constant after about 20 years (Beardsley, 2006). The study also found that particulate matter emissions increase exponentially with vehicle power (or road or engine load). The EPA found that emission data for heavy-duty vehicles are not sufficient to permit stratification according to engine size, vehicle weight, and injection type (direct and indirect) (U.S. EPA, 2009b). Emissions from road vehicles are calculated using the emission factors defined by the EPA under the MOBILE program.

The approach adopted in the European Environment Agency (EEA)/United Nations Economic Commission for Europe (UNECE) Cooperative program for monitoring and evaluating the long-range transmission of air pollutants in Europe (known as EMEP) (EEA, 2009, 2007 and 2005) considers passenger cars, light duty vehicles, heavy-duty vehicles, and motorcycles and mopeds. It covers gasoline, diesel, LPG, and natural gas fuels. The EMEP system assumes that all particulate matter is $PM_{2.5}$, as it is assumed that the coarse fraction is negligible in vehicle exhaust. This is consistent with the findings of Ristovski et al., (1998) who found that the mean particle diameter in emissions from gasoline-fueled vehicles was below 1µm.

When estimating airport-related air emissions resulting from surface traffic and other road vehicles emissions, EDMS calls upon the EPA's MOBILE6.2 emission factor model at the national default level. This provides emission factors in grams per vehicle miles traveled (VMT) for gasoline and diesel-fueled road cars, trucks, buses, motorcycles and other vehicles. It should be noted that while EDMS continues to use MOBILE, this model has now been replaced outside EDMS by a newer regulatory model, the Motor Vehicle Emission Simulator (MOVES) (U.S. EPA, 2010c). However, for consistency with the EDMS model, the ACRP 02-23 project used MOBILE 6.2. The current version of the MOVES model includes a number of alternative fuel emission factors, such as gasoline, diesel, CNG, LPG and electricity (U.S. EPA, 2010f). It is intended that MOVES will eventually include other fuels, such as ethanol (E85), methanol (M85), gaseous hydrogen, and liquid hydrogen (U.S. EPA, 2009c), but it did not at the time this report was written.

MOBILE6.2 can also be run independently of EDMS, the results of which can then be re-incorporated into EDMS, to account for area specific parameters (e.g., local registration data, VMT data, emissions control program parameters, meteorological data and sulfur fuel content) that may have been established by state air quality agencies in non-attainment areas, or other considerations. In addition, MOBILE6.2 (U.S. EPA, 2003a and 2003b) assumes that the total exhaust particulate matter is made up of three factors for recent years (assumes no lead): organic derived particulate matter, elemental particulate matter, and sulfur-derived particulate matter. For gasoline, the first two factors are combined (due to lack of separate data). However, for diesel, all three factors are separate. MOBILE also calculates brake and tire wear particulate matter. MOBILE6.2 also includes estimated particulate matter from natural gas vehicles (NGVs) by assuming the particulate matter emissions are, in essence, the same as those for very low-sulfur gasoline. Therefore, it is possible to alter the diesel sulfur content in the input file for MOBILE (this must be done outside EDMS) and then use the new output emission factors in their composite form in EDMS. It is also possible to alter the assumed market shares of ether and ethanol blends in MOBILE. Similarly, the output files from MOBILE can be used to estimate the different components of the composite particulate matter emission factor used in EDMS. Therefore, some volatile emissions can be split out, although it will not include the organic volatile emissions from gasoline vehicles due to the combined nature of gasoline organic and elemental particulate matter.

Brake and Tire Wear

Research carried out by the EPA indicates that 10% of brake wear particulate matter is $PM_{2.5}$ (Nam and Srivastava, 2006). The EPA data suggest that the MOBILE model used by EDMS is likely to underestimate brake and tire wear emissions. For example, a simple study, using default factors within EDMS, generated the emission factors in MOBILE where brake and tire wear accounted for around 17% of $PM_{2.5}$ emissions. A much smaller proportion of PM_{10} (less than 0.1%) was reported in a study of tire wear from motorcycles and small cars traveling at constant speeds on a concrete surface (Aatmeeyata and Kaul, 2009). The reason for this discrepancy is not clear, although this could be due to the sizes of the vehicles and the roadway surface.

The emission factors (in g/km) for brake and tire wear used in the UK National Atmospheric Emissions Inventory (NAEI) are described in the Air Quality Expert Group (AQEG) report on particulate matter (AQEG, 2005). The methodology draws on a review of brake and tire wear carried out for UNECE, which has informed the methodology included in the recent versions of the European EMEP/CORINAIR Emission Inventory Guidebook (EEA, 2005). These emission factors indicate that the UK and European methodology assumes much higher factors for tire wear than that assumed in the U.S.

ROAD VEHICLE ALTERNATIVE FUELS

The U.S. DOE defines the following alternative fuels for vehicles under the Energy Policy Act (1992) (U.S. DOE, 2010): biodiesel, electricity, ethanol, hydrogen, methanol, natural gas, and propane. Several emerging fuels are currently under development and are also regarded by DOE as alternative fuels. These include biobutanol, biogas, BTL, CTL, FT diesel, GTL, hydrogenation derived renewable diesel, P-Series, and ultra-low-sulfur diesel.

The EPA carried out a measurement survey that confirmed the beneficial effect of biodiesel mix on emissions of particulate matter from diesel-fueled vehicles (U.S. EPA, 2002b). The effect on particulate matter and other emissions is given by the following equation:

$$\text{Change in emissions} = e^{-0.06384 \times \%B} \qquad \text{where B is between 0 and 100 (percent biodiesel)}$$

The European EMEP inventory (EEA, 2009, 2007 and 2005) provides guidance on the effect of biodiesel blends on emissions of particulate matter. For older diesel technologies with no advanced combustion concepts and after-treatment systems, biodiesel may lead to a higher proportional reduction in emissions of particulate matter because the presence of a carbon-oxygen chemical bond reduces the particulate matter formation by intervening in the chemical formation process.

For more recent technologies with ultra-high-pressure combustion and after-treatment, the biodiesel effect is difficult to predict because of changes in physical properties of the fuel.

The European EEA estimates that biodiesel blends B10 and B20 reduce vehicle particulate matter emissions by between 10% and 20% (Table 3-104: EEA, 2009, 2007 and 2005). This is a slightly greater decrease in emissions than that reported by the EPA. For heavy-duty vehicles, the estimated reduction in emissions for B100 is 47%, identical to that reported by the EPA. The DOE suggests that pure biodiesel (B100) greatly reduces emissions other than NO_x and that B100 could potentially be used advantageously by professional fleets with appropriately equipped maintenance departments.

The Argonne National Laboratory found that vehicles that, effectively, have zero tailpipe emissions could have relatively high or relatively low particulate matter emissions when considered on a life-cycle basis (Argonne, 2005). The use of renewable versus non-renewable sources of electricity was found to be an important factor. Liquid hydrogen fuel-cell vehicles performed relatively well, whereas a gaseous hydrogen internal combustion engine performed relatively poorly.

A literature review carried out for the Dutch government found a mixed picture in terms of the effects of biofuels on emissions of particulate matter (TNO, 2004). Ethanol, FT diesel, and bioDME (dimethyl ether) were found to result in reduced emissions of particulate matter. Biogas was found to result in low emissions, but with a risk of higher emissions if product quality is variable. The picture for biodiesel is not straightforward. The low sulfur content of biodiesel, FT diesel and bioDME would be favorable for the use of catalytic converters, if used. Using biofuels can result in operational difficulties with associated emissions issues (e.g., ethanol can act as a solvent for past gasoline deposits), but such issues can generally be overcome. The effects of biofuels on emissions of other non-regulated pollutants (e.g., individual potentially hazardous volatile organic compounds (VOC)) are favorable overall.

A review carried out for the European Commission also investigated the effects of biofuels on emissions (JNC, 2006). Using pure biodiesel was found to have a mixed effect on emissions from heavy-duty vehicles, with reductions up to 80% and increases up to 40%. Increases were observed for biodiesels with a higher soluble organic fraction. Biodiesel blends generally resulted in a reduction of particulate matter of up to 50%. Using vegetable oils in heavy-duty vehicles was found to have a mixed effect on emissions of particulate matter. The European Commission study also reported research which indicated that alternative fuels may reduce particulate matter emissions from light duty vehicles under fuel-rich driving conditions, such as heavy accelerations. Emissions of particulate matter increased in order from LPG, CNG, 85% ethanol with 15% gasoline, 85% methanol with 15% gasoline, to the highest emissions from reformulated gasoline.

A detailed review of the effects of biodiesel on diesel engine emissions found that 95% of publications report a decrease in particulate matter emissions with biofuel compared with diesel and 3% report an increase (Lapuerta et al., 2008). The study found that most authors have reported increases in the number of small particles with the use of biodiesel, with most particles smaller than $PM_{0.1}$. For example, Wang et al., found that B35 biodiesel resulted in a 25% reduction in emissions of particulate matter, consistent with the above EPA formula (Wang et al., 2000). These authors considered that the reduction was due mainly to the oxygen content of biodiesel, and also to the lower sulfur and aromatic content of biodiesel.

A UK study reviewed a wide range of emissions studies and provided an assessment of the effect on particulate matter emissions compared with a reference fuel (gasoline or diesel) for use in emissions inventory compilation (AEA, 2008). No correction for sulfur content is provided. The estimated factors are set out in Table 3 in Chapter 2 of this report and are comparable to those set out in the above equation.

Reductions in particulate matter emissions were confirmed in a study carried out for the World Bank (Kojima and Johnson, 2005). A study of biomass-to-liquid fuels provided a comparison of emissions reduction from BTL and GTL (i.e., FT) diesel compared with oil derived diesel (Kavalov and Peteves, 2005). This indicated that biomass-derived diesel delivers about a 25% to 65% improvement in $PM_{2.5}$ emissions, and FT diesel delivers a 26% to 50% reduction. This study indicates that bioDME can deliver up to 90% reductions in emissions of NO_x and particulate matter. This is supported by measurement data, including data from the U.S. (Norton et al., 1998; Muncrief et al., 2007).

Use of methanol, ethanol, and methyl tertiary butyl ether as fuels can lead to increases in secondary particulate matter due to the formation of peroxy acetyl nitric acid (PAN) (Gaffney and Marley, 2009).

The data discussed and presented above could be used to generate proxy alternative fuel emission factors for road vehicles and GSE.

The data for the use of biodiesel blends are summarized in Figure 6 in Chapter 2 of this report.

OTHER EMISSION SOURCES

“Other” emissions refers to emissions from on-airport sources other than the major sources discussed above (aircraft, APU, GSE, and road vehicles). This category includes emissions from:

- Heating plant
- Training fires
- Aircraft maintenance activities
- Fugitive emissions from fuel handling (aircraft and vehicular)
- Construction activities

The range of sources is wide if fugitive VOC emissions are considered in the context of particulate matter emissions. However, heating plant and training fires are typically the main sources of “Other” (i.e., not aircraft, GSE or road vehicles) particulate matter. Therefore, these sources are the principal focus here. However, construction emissions are also an important source of particulate matter, though, by their nature, they tend to be limited to the period of construction. Therefore, they are not addressed further in the ACRP 02-23 project.

It may also be convenient to identify source categories, such as the additional emissions arising from cold starts in airport parking lots, queuing taxis, and idling buses and coaches, that require a different emissions methodology from the one used for road vehicle emissions on the landside roadway network. Nevertheless, it is assumed here that these sources are included in the principal road vehicles source category discussed above.

Types of other sources included in EDMS include heating and power raising (boilers and incinerators fueled by coal, oil, gas, LPG or general waste), emergency generators (fueled by gas, oils or LPG), aircraft engine testing (in essence, covered in the aircraft section), deicing, fuel tanks and solvent use. Deicing, fuel tanks and solvent use are not directly related to particulate matter, although the fugitive VOC emissions from these sources could potentially cause $PM_{2.5}$ emissions. However, in EDMS only VOC is included as a pollutant for these sources, and it should also be considered that their contribution to total $PM_{2.5}$ is likely to be relatively small. Stockpiles of things such as salt and sand are included in EDMS. Including these sources does result in $PM_{2.5}$ emissions, though these are not impacted by alternative fuels.

Conventional Fuels – Heating Plant Emissions

The term “airport heating plant” is used as shorthand for an on-airport plant using local combustion of fuel to produce heating and/or electrical energy. While electricity provided to the airport from the grid also creates emissions, they are assumed to be non-local to the airport.

Emissions data for heating plant stationary sources are provided by the EPA in its *Compilation of Air Pollutant Emission Factors* (U.S. EPA, 2010g), and that data are used as a basis for the EDMS emission factors. Traditionally, commercial and industrial boilers have been used to supply space heating and hot water to passenger terminals, commercial buildings, and maintenance hangars, and are fired by gas or fuel oil (either distillate oil, sometimes called “gasoil” or heavy fuel oil). Particularly when fired by liquid fuels, such plant may constitute one of the largest sources of annual particulate matter emissions at an airport. However, stack design usually ensures that those emissions do not make a major contribution to off-airport airborne ambient particulate matter concentrations. However, if there are residential population areas close to the airport perimeter, the details of stack efflux characteristics may play a critical role in ensuring that the contribution from this source is minor. Natural gas, which, as a fuel, has relatively few associated particulate matter emissions, is currently used at a large number of U.S. airports (Lau et al., 2010).

Besides conventional boilers, an alternative type of plant used at airports for heat and energy generation is combined heat and power (CHP) plant. Various types of CHP plant have been used or considered for airports, such as conventional turbines fueled by gas and/or gasoil, converted aircraft engine turbines fueled by kerosene and large diesel engines. It should be noted that representative (default) particulate matter emission factors for turbines (in g/MJ) are usually somewhat higher than those for conventional boilers. However, in practice, the emission factors vary widely with details of the plant design and the type of control technology implemented.

Conventional Fuels – Training Fire Emissions

Major airports must have on-airport facilities for firefighting and rescue, in accordance with ICAO requirements, and must make provision for fire training. The emissions associated with fire training are commonly included in airport emissions inventories for completeness. However, in annual terms, they comprise a very small fraction of the total near ground particulate matter emissions on the airport. Conventionally, kerosene has been used to create training fires to ensure realistic fire temperatures and smoke densities but, more recently, kerosene has been replaced by other fuels at some airports.

Even with kerosene fuel, the estimated annual particulate matter emissions from fire training exercises are a small fraction of the total on-airport particulate matter emissions. Of course, the emissions derive from a relatively small number (typically tens) of training exercises in the year, so the chief health concern may relate to short-term concentrations during the exercises rather than the contribution to long-term exposure. Nevertheless, 24-hour 98th percentile off-airport particulate matter exposures on fire training days are not likely to be demonstrably higher than those experienced on other days.

Alternative Fuels – Heating and Power

As discussed previously, the AP-42 includes emission factors and methodologies for calculating a wide variety of heating plant emissions for different fuel types, many of which are incorporated in EDMS. However, although heating plant emissions are unlikely to make a major contribution to off-airport ground level airborne particulate matter concentrations, there may still be an interest in reducing emissions per se. This is particularly the case if there are targets and limits on the overall emissions burden of the airport in addition to limits on ambient airborne concentrations.

A change of fuel may arise as a consequence of a complete change of heating plant type (e.g., from boilers to CHP or from large diesel engine CHP to gas turbine CHP). This type of replacement may be driven primarily by economic considerations, but could have a beneficial impact on particulate matter emissions if the plant is chosen carefully. An example of a simple change to a less conventional fuel type would be a switch to LPG in boilers or turbines. The use of LPG could yield a high reduction in particulate matter emissions over fuel oil, so it could provide an alternative in situations where a network gas supply is not available.

There are other motivations for changing the type of fuel and/or type of plant to supply heating and energy on an airport in addition to economic considerations and the desire to reduce local air quality pollutant emissions. In recent years, an important driver of change has been the desire to reduce the airport's carbon footprint, and biomass-fueled plant are increasingly being considered as a replacement for existing plants or as a supplement to meet the requirements of airport expansion. However, a modern wood burning plant is likely to produce much higher particulate matter emissions than those produced by a gas fired boiler or turbine, so there is likely to be a trade-off between carbon footprint and air pollutant emissions.

Similarly, airports create large volumes of mixed waste, and energy from waste (EfW) plants is an attractive way to reduce waste volume while supplying some of the energy requirements of the airport. However, once again, they could increase particulate matter emissions where the increase depends on the type and size of plant, and on the sophistication of the emissions control technology implemented. Furthermore, if the energy generated replaces electricity from the grid, all of the emissions produced represent an addition to the local emissions inventory.

There are options for meeting an airport's heating requirements that do not depend on combustion so, in principle, they generate virtually no local air pollutant emissions in operational use. Examples include solar photovoltaic at Phoenix Sky Harbor International (PHX) and Fresno Yosemite International (FAT) airports, solar thermal heating at Dallas Fort Worth International Airport (DFW), and wind turbines at Minneapolis-St. Paul International Airport (MSP). Other options also include geothermal and ground source heat pumps, co-generation, and thermal storage (peak shifting) (Lau et al., 2010). However, the practicability of such options depends on location and economic viability. Of course, general best practices for energy management, insulation, etcetera, which are not the subject of this report, will reduce energy consumption and the resulting particulate matter emissions.

Alternative Fuels – Training Fires

The smoke pollution caused by the open burning of kerosene has led some airports to turn to alternative fuels, although there are no statistical data on how widespread the switch from kerosene has been. At the major London airports in the UK (Heathrow, Gatwick, and Stansted), LPG burners have been used for fire training, although small amounts of kerosene may still be burned for specific training exercises. Although particulate matter emission factors for the open burning of kerosene and for LPG burners of the type used for training fires are not well characterized, LPG fueling clearly produces much less visible smoke and can be assumed to generate much lower particulate matter emissions. EDMS includes emission factors for JP-4, JP-5, JP-8, propane (LPG), and tekflame. Tekflame and LPG theoretically produce fewer particulate matter emissions than the other more conventional fuels, according to the EDMS model.

DISPERSION MODELING AT AIRPORTS

According to FAA Order 1050.1E Change 1, dispersion models prepared for the evaluation of airport air quality impacts must be prepared using EDMS (version 5.1.2.). EDMS typically invokes EPA's AERMOD dispersion model to translate the emissions inventories it calculates into predicted concentrations of air pollutants in the study domain. AERMOD/EDMS incorporates information on the spatial arrangement and emission characteristics of airport sources, terrain and elevation, meteorological variables, and other physical considerations when predicting concentrations. However, it should be noted that AERMOD is a short-range dispersion model used to assess local air quality impacts and does not include chemical interactions that result in the formation of secondary atmospheric particulate matter. When using EDMS/AERMOD, secondary particulate matter can only be accounted for by adding a background particulate matter component. This section outlines some recent and pertinent environmental studies at airports that included dispersion modeling as part of a National Ambient Air Quality Standards (NAAQS) assessment required by the National Environmental Policy Act of 1969 (NEPA) or were recommended due to agency and/or public concerns.

Hartsfield-Jackson Atlanta International Airport (ATL)

Unal et al., (2005) studied air quality impacts in the Atlanta ozone (O_3) and particulate matter non-attainment area in relation to ATL aircraft and GSE operations. Emissions were calculated using an older version of the FOA (not FOA3) methodology within EDMS version 4.01, whereby $PM_{2.5}$ emissions are computed as a function of an aircraft engine’s SN and fuel flow rates. The analysis tested two approaches with respect to SN, one of which applied a “characteristic” SN for each engine, while the other applied a mode specific SN to account for differences in engine power applied during flight procedures. Finally, the emissions were applied to a dispersion model to apportion the results relative to other sources operating in the non-attainment area, as well as to discern what sort of impact ATL has on ambient $PM_{2.5}$ concentrations in its vicinity.

The dispersion model indicates that ATL aircraft contribute up to 0.13% of the total $PM_{2.5}$ emissions burden in the area, non-airport area sources comprise over 90%, nonroad equipment (besides GSE) contributes 4.5%, and GSE contributes only 0.05%. Moreover, the dispersion model indicates that when using the “characteristic” SNs, the airport contributes 25 $\mu g/m^3$ to the modeled concentrations at the receptor of maximum impact, although predicted concentrations are typically highly variable depending on receptor location. When applying the mode specific SNs, the impact of ATL is reduced to around 1 $\mu g/m^3$ at the receptor of maximum impact. GSE also contributes an additional maximum 9 $\mu g/m^3$ of $PM_{2.5}$ to the modeled concentrations within 16 km of the airport property in both scenarios.

O’Hare International Airport Modernization Program (ORD)

$PM_{2.5}$ dispersion modeling was conducted in support of the ORD Modernization Program environmental impact statement (EIS) using EDMS (U.S. EPA, 1999). In this analysis, background concentrations were developed using monitoring data available from the Illinois Environmental Protection Agency (IEPA), corresponding to 35.2 $\mu g/m^3$ for evaluation against the 24-hour standard and 13.3 $\mu g/m^3$ for comparison against the annual NAAQS. Fifty-three discrete receptors were placed around the airport property line and along the terminal areas. Dispersion modeling was conducted for all development alternatives under consideration as required by NEPA, with some minor variations resulting from different development scenarios.

Philadelphia International Airport Capacity Enhancement Program (PHL CEP)

As part of the PHL CEP EIS, dispersion modeling was conducted at PHL using EDMS to ascertain whether the planned improvements associated with PHL CEP would cause or contribute to existing or additional infractions of the $PM_{2.5}$ NAAQS (U.S. FAA, 2010c). Thirty-two discrete receptors were placed around the airport property at assumed areas of maximum impact on sensitive populations, including at terminal curbsides, runway ends, and in surrounding nearby residential or public use areas. For evaluation against the 24-hour $PM_{2.5}$ NAAQS, a background concentration of 36.9 µg/m^3 was applied based on available monitoring data for evaluation against the annual $PM_{2.5}$ NAAQS, a background concentration of 15.0 µg/m^3 was used. The results indicated that the point of maximum impact under the no action alternative was located at the receptor placed along the Terminal B and C curbside, returning predicted concentrations of 47.1 µg/m^3 and 17.8 µg/m^3 relative to the 24-hour and annual standards respectively (background inclusive). Under the preferred development option, the point of maximum impact in the build-out year 2025 shifted to the receptor located at the general aviation (GA) tarmac, with predicted concentrations of 43.5 µg/m^3 and 16.6 µg/m^3 relative to the 24-hour and annual standards respectively (background inclusive). With respect to the preferred development option in the build-out year (2025), the points of maximum impact shifted to the receptor located at the Centralized Headhouse surrounding Terminals 3 and 4, with predicted concentrations of 41.8 µg/m^3 and 16.2 µg/m^3 relative to the 24-hour and annual standards respectively (background inclusive).

It was concluded that, under the preferred alternatives, emission sources at PHL would contribute between 1.3 µg/m^3 and 1.6 µg/m^3 to the annual average concentration of $PM_{2.5}$ (or about 8% to 9% of the total concentration), while the remaining concentrations were attributed to background sources.

Providence T.F. Green Airport (PVD)

In a similar way to the PHL CEP EIS, the PVD EIS (published in 2010) sought to evaluate the air quality impacts of the planned developments at the airport using a dispersion model prepared using EDMS (U.S. FAA and RIAC, 2010). The background concentrations used in the analysis were reportedly 31.1 µg/m^3 and 10.6 µg/m^3, respectively, for the 24-hour and annual $PM_{2.5}$ NAAQS. Overall, the analysis concluded that in the build-out year 2025, the point of maximum impact would occur proximal to the main terminal building, with predicted concentrations equaling 34 µg/m^3 for the 24-hour standard and 12 µg/m^3 when considering the annual standard.

APPENDIX B: CASE STUDY AIRPORTS

This Appendix discusses the detailed methodology used to determine the five case study airports for the ACRP 02-23 project. These five airports were considered to offer the best opportunities to produce meaningful results for the ACRP 02-23 project. The underlying data tables are included towards the end of this Appendix.

EVALUATION CRITERIA

The evaluation criteria used in identifying, evaluating and selecting the case study airports were initially identified in the *Proposal* and restated in the *Working Plan* approved by the Project Panel for the ACRP 02-23 project (PPC, 2010). As such, these criteria and their application are considered to be among the most important in evaluating the impacts of airport-related fine particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) emissions on local air quality and assessing the potential benefits of alternative fuels on these conditions. Although it is recognized that other evaluation criteria may exist, they were not viewed as crucial.

AIRPORT ACTIVITY LEVELS

The Federal Aviation Administration (FAA) classifies U.S. airports that provide scheduled passenger services and have over 10,000 annual passenger boardings (i.e., enplanements) per year as *primary* airports. According to the FAA, there are 388 primary airports in the U.S. As a means of reducing the size of this list of potential candidates and more effectively applying the evaluation criteria, the median enplanement and operational levels of this group served as the threshold for this assessment. In other words, airports with enplanement and operational levels greater than 135,000 and 58,000, respectively, were included in the initial list of candidate airports. Below this level of enplanements it was judged unlikely that the airport would be contributing significantly or measurably to ambient $PM_{2.5}$ concentrations.

From this initial screening, 138 airports met the median enplanement and operational criteria. These airports range from Hartsfield-Jackson Atlanta International Airport (ATL) with nearly one million aircraft operations to Lincoln Airport (LNK) in Nebraska with about 70,000 operations. These encompass airports of all hub sizes, operational types, geographic locations and meteorological conditions throughout the U.S.

For the purpose of the ACRP 02-23 project, these 138 airports were identified as “first-order airports” and were subjected to the remaining evaluation criteria.

AVAILABILITY AND APPROPRIATENESS OF DATA

Sources of Airport $PM_{2.5}$ Emissions

Among the “key” elements of the ACRP 02-23 project is the assessment of airports’ contribution to $PM_{2.5}$ levels, by emission source type. However, most airports comprise a varied and unique assortment of emissions sources, each with its distinctive set of $PM_{2.5}$ emission rates, $PM_{2.5}$ formation mechanisms and $PM_{2.5}$ transport characteristics. Therefore, to properly account for the various sources of $PM_{2.5}$ emissions associated with airports, the emissions and operational data for the following are required:

- Aircraft
- Auxiliary power units (APUs)
- Ground support equipment (GSE) (e.g., belt loaders, baggage tugs, aircraft tugs)
- Road vehicles (e.g., private automobiles, shuttle vans, taxis, buses)
- Stationary sources (e.g., boilers, cooling towers, emergency generators, fire training, incinerators)

Types of Airport $PM_{2.5}$ Assessments

There are also three categories (or types) of "assessments" that are considered necessary for quantifying the local impacts of $PM_{2.5}$ from these airport-related emission sources. Each data set is used in different ways, and has its own particular applications and limitations, which include:

- **Air emissions inventory data** – used to quantify the total amount of emissions (referred to as mass, because it considers the molecular weight of the quantity of pollutants measured) of individual sources in a defined study area (commonly expressed in tons/year, tons/day, pounds/hour).
- **Atmospheric dispersion modeling data** – used to estimate the pollutant concentrations in the ambient (i.e., outdoor) air. Concentrations refer to pollutant levels that an individual would be exposed to at a specific location in the study area (commonly expressed as micrograms/cubic meter ($\mu g/m^3$).
- **Air quality monitoring data** – actual measurements of ambient pollutant concentrations at a specific location (again, commonly expressed as $\mu g/m^3$). Although useful, the data do not readily enable the apportionment of the concentration by source.

Airport $PM_{2.5}$ Assessment Data Needs

To develop these assessments, specific sets of data are necessary, often involving extensive data gathering and development efforts such as traffic surveys, airfield simulation modeling, and on-airport surveys. Given the financial resources and timescales to obtain these data (i.e., months and years), this was considered beyond the scope of the ACRP 02-23 project. Therefore, relative to the objectives and design of the ACRP 02-23 project, the most important data needs included the following:

- Aircraft fleet mix, aircraft taxi and delay times, taxiway and runway configurations, primary taxi paths (arrival runway end to terminal to departure runway end), airfield coordinates, runway use, and temporal (i.e., hourly, daily, and monthly) operational profiles
- Information on gate power and/or pre-conditioned air
- GSE fleet, fuel type, equipment size, operating conditions, time of operation, and location of aircraft servicing (often by terminal area)
- Road vehicle traffic volumes and operating characteristics (i.e., roadway, parking lot and curbside configurations, emission factors)
- Stationary source use, equipment size, fuel type, exhaust release parameters and location
- Meteorological data (e.g., wind speed, direction)

Again, given the manpower, time and other resources required to obtain or develop these airport-specific "source" and "assessment" data, the availability, age, and comprehensiveness of any existing data were considered to be among the most important factors for selecting candidate airports. For this reason, a search was conducted to determine which of the first-order airports had conducted air quality studies that were reasonably recent and had datasets that were potentially useful to the ACRP 02-23 project. This information was identified as essential, as the ACRP 02-23 project was not scoped to generate this information for the requisite candidate airports.

Prepared for environmental impact evaluations under the National Environmental Policy Act (NEPA) or similar state level programs, as part of a State Implementation Plan (SIP) or in support of other airport-specific environmental initiatives (e.g., air quality management plans), these air quality studies were combined with expert knowledge of other potential sources of information and data. From this research, it was determined that 30 airports had air quality information in terms of emissions inventories, dispersion analyses and local background information that could be of some potential use to the ACRP 02-23 project. For the purposes of this assessment, these 30 airports were called “second-order airports.”

DATA RATING INDEX

To better define the value of the data, the second-order airports were assigned a data rating index (DRI) ranging from A through E representing the data type (i.e., emissions inventory, dispersion modeling and/or ambient monitoring), the availability of data and the timeliness of the data. Developed specifically for this project, Table 10 presents a description of the DRI. Many of these data elements are related to specialized studies, and it was not expected that all airports would have the information. Rather, the rating used here was designed to help show which airports already had information necessary and was not intended to be a critique of the analysis completed for any airport.

By way of example, Providence T.F. Green Airport (PVD) recently completed a comprehensive emissions inventory and dispersion modeling analysis for airport sources, operates a number of $PM_{2.5}$ monitoring stations near the airport and data were readily available. Thus, PVD received a DRI of “A” with respect to the ACRP 02-23 project. By comparison, Minneapolis-St Paul International Airport (MSP) conducted an ambient monitoring study in 2002, but no further publicly available airport emissions inventory and dispersion modeling analyses were found. Thus, MSP received a DRI of “E.”

Table 10 – Data Rating Index (DRI)

Rating	Description
A	Data are available in two or three of the desired categories (i.e., emissions inventory, dispersion modeling and air monitoring). Data are recent, contain airport-specific information, and are readily available.
B	Data are available in one or two of the desired categories. Data are recent, contain airport-specific information, and are readily available.
C	Data are available in one or two of the desired categories. Data are either not recent, do not contain airport-specific information, and/or are not readily available.
D	Data are available in one of the three categories. Data are not recent, do not contain airport-specific information, and are not readily available.
E	Data are not available or limited in desired categories. Data are not recent, do not contain airport-specific information, and are not readily available.

With respect to atmospheric dispersion modeling data, airport air quality assessments that also contain airfield simulation modeling results from models such as the Total Airspace and Airport Modeler (TAAM) or Airport and Airspace Simulation Model (SIMMOD), combined with airport-specific GSE and APU use data, and surface traffic were considered more desirable for the ACRP 02-23 project due to the higher level of accuracy.

Based on data availability and the DRI outcomes, a total of 16 airports with DRIs of A, B or C were identified and designated as “third-order airports” (Figure 16). These airports were considered to be good candidates for the ACRP 02-23 project and were further evaluated as part of the screening process as discussed in the following sections.

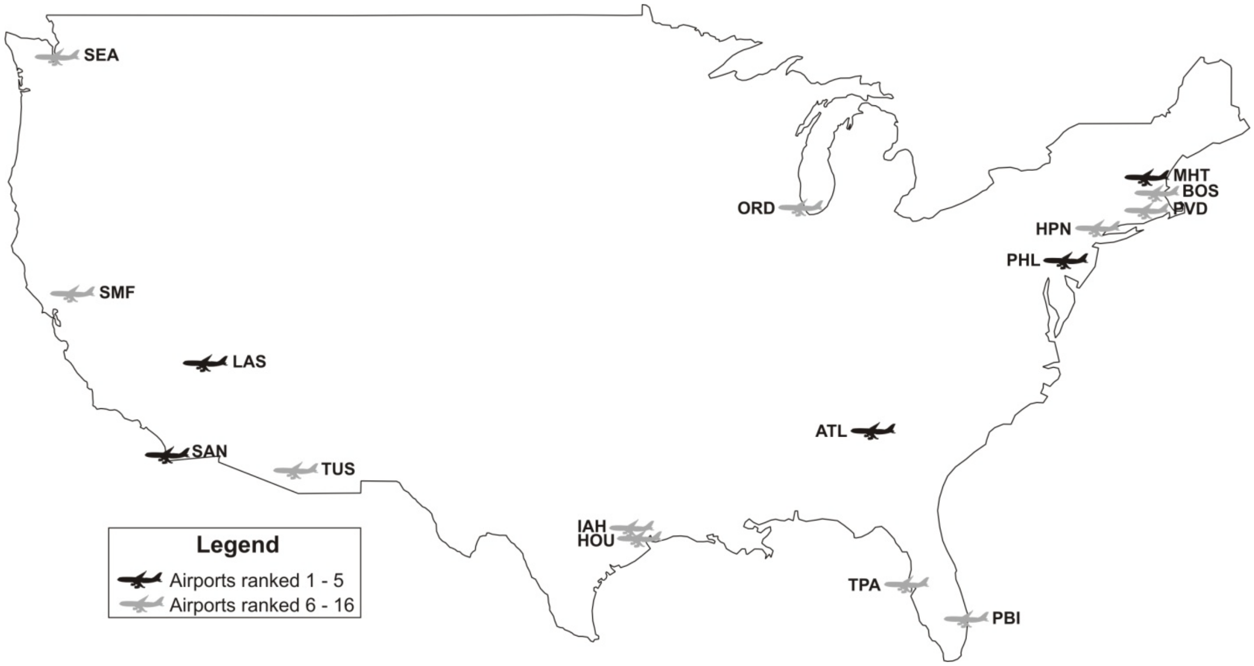


Figure 16 – Candidate Case Study Airports

PRIMARY EVALUATION CRITERIA

The following were considered to be among the most important characteristics (i.e., primary criteria) for a case study airport:

- Availability of existing, recent and appropriate air quality assessment data
- Willingness to participate in the ACRP 02-23 project
- Current or planned alternative fuel program
- Representative of other airports based on size, location, climate, etc.
- $PM_{2.5}$ non-attainment status

Airport Willingness to Participate

While every airport that was contacted expressed support for this project, some did not have the staff resources or capability to support this research or the required data. The ability to provide assistance was then considered for purposes of this study “willingness to participate” and represented an important criterion to enable the ACRP 02-23 project to be completed on time and on budget. Without this first-hand involvement and cooperation, many of the other factors (e.g., availability of data, attainment/non-attainment status, activity levels, meteorological conditions) were considered of reduced value to the ACRP 02-23 project. The reasons most likely to motivate an airport to serve as a case study airport included the following:

- Contribute to and help advance environmental research.
- Improve agency and public relations.
- Obtain information about $PM_{2.5}$ data at the airport.
- Assess the potential benefits of an existing or planned alternative fuel program.

Promises of cooperation were received from the following airports:

- Hartsfield-Jackson Atlanta International Airport
- Las Vegas McCarran International Airport
- Manchester-Boston Regional Airport
- Philadelphia International Airport
- San Diego International Airport

Alternative Fuels Programs, Plans, and Interests

Consistent with the principal aim of the ACRP 02-23 project, airports actively considering or implementing alternative fuel programs were identified. Based on expert knowledge, the following airports were identified as being representative (but not inclusive) of this group:

- **Hartsfield-Jackson Atlanta International Airport** – strong interest from Delta Airlines and State of Georgia in an alternative fuels project
- **Detroit Metropolitan Airport** – alternative fuels and feedstock study underway
- **Denver International Airport** – solar panel projects in place and underway
- **Los Angeles International** – state-mandated conversion program to convert GSE to no- and low-emitting fuels
- **Port Authority of New York and New Jersey** – has launched a study to implement a municipal solid waste (MSW) to liquid fuel project
- **Seattle-Tacoma International Airport** – actively participating in alternative fuel projects

$PM_{2.5}$ Attainment/Non-attainment Areas

The $PM_{2.5}$ National Ambient Air quality Standards (NAAQS) attainment/non-attainment status of an area is important in the context of federal and state air quality regulations, SIP requirements and timetables, and the potential eligibility for the funding of alternative fuel initiatives such as the FAA Voluntary Airport Low Emissions (VALE) program for non-aircraft sources.

Figure 4 and Figure 5 in Chapter 1 display areas of the U.S. currently in violation of the annual and 24-hour $PM_{2.5}$ standards, respectively, based on recent air monitoring data. As shown, non-attainment areas are generally located in California, mid-Atlantic, Midwest, Utah, and southeastern states.

Of the 16 third-order airports, the following were assessed as being located in $PM_{2.5}$ non-attainment areas:

- Hartsfield-Jackson Atlanta International Airport
- Chicago O’Hare International Airport
- Philadelphia International Airport
- Sacramento International Airport
- Westchester County Airport

Therefore, these locations were more likely to consider the value of different $PM_{2.5}$ emissions reduction actions in the future, possibly including alternative fuels.

SECONDARY EVALUATION CRITERIA

In addition to the primary evaluation criteria, the following secondary criteria were also considered when evaluating potential case study airports:

- Meteorology, climate and geography
- Airport operational parameters
- Demographics and land use
- $PM_{2.5}$ ambient monitoring data

Meteorology, Climate and Geography

Meteorological conditions (e.g., wind speed, wind direction, temperature, relative humidity, atmospheric mixing height, precipitation, sunlight) play important roles in the formation and dispersion of air pollutants (including $PM_{2.5}$), both regionally and locally. Climatic (e.g., continental, oceanic, mountainous) and geographic (e.g., latitude, elevation) conditions can also have an effect on fuel combustion, fuel type and fuel use, and can influence the feasibility of an alternative fuel.

For the ACRP 02-23 project, these parameters were generally categorized as “cold,” “temperate,” or “warm” based on an airport’s annual average temperature compared with the nationwide annual average. These were defined relative to the average temperature within continental U.S. (53.1ºF or 11.72 ºC) during 2009. Temperate was defined as within 2.5ºF (1.34 ºC) of the average, cold at or below 50.6ºF (10.33 ºC), and warm at or above 55.6ºF (13.11 ºC). Other meteorological data such as the number of days with temperatures greater than 90°F, the number of days with temperatures less than 32°F, average wind speed, the number of days with measureable precipitation, the average annual relative humidity, the percent of time the sun shines, and the number of heating and cooling degree days (HDD/CDD) were also considered.

This information was used to identify candidate case study airports that would be representative of other airports that have similar meteorological, climatic, and geographic characteristics.

Airport Operational Parameters

Beyond the selection of potential case study airports based on operational levels discussed previously, the range and variation of the airport's operational parameters are also considered important when trying to account for the application and transferability of the ACRP 02-23 project to other airports.

Activity levels (e.g., aircraft landing and takeoff (LTO) cycles or enplanements) can vary widely among different commercial airports. These operational levels can also vary significantly at the same airport both temporally and spatially based on the season, runway layout, meteorology, and noise abatement procedures. As such, these factors are considered to be important when assessing the effects of $PM_{2.5}$ on local air quality.

For this assessment, airport operational and enplanement data were used as an indicator of airport activity levels (U.S. FAA, 2010d and 2010e). Similarly, an airport's hub size (i.e., large, medium or small) was used to further categorize these airports. The types of aircraft at an airport were also considered to be an important factor, and range from commercial, commuter, air taxi, general aviation (GA), and military.

Additionally, because aircraft $PM_{2.5}$ emissions are most notable in the taxi operating modes, data related to an airport's taxi and ground delay time on arrival and departure (U.S. FAA, 2010f) were considered important.

This information was used to identify candidate case study airports with a variety of operational levels and aircraft categories that would be representative of the airports in the nationwide airport system.

$PM_{2.5}$ in the vicinity of most commercial airports occurs at low levels and the particles are nearly indistinguishable from those that are associated with non-airport sources. Therefore, the assessment of the airport operational parameters mainly focused on the following:

- Airports with activity levels sufficient enough to generate "measurable" air quality impacts
- Airports with activity levels that best represent the range of facilities that will benefit from this research (i.e., large, medium, or small)
- Airports with representative aircraft GSE types
- Airports with representative operational characteristics (i.e., taxi and ground delay time)

Notably, even though GA airports are not specifically included, some of the candidate airports have significant GA fleets.

Demographics and Land Use

Notwithstanding land use regulations that aim to guide compatible development around U.S. airports, population densities adjacent to many of these facilities are increasing, especially near some of the oldest (e.g., Chicago-Midway, Providence T.F. Green, Dallas Love Field) and newest (e.g., Denver) facilities. Pollutant exposure to airport-related emissions is second only to noise as the principal health concern among people that live and work near airports. This is especially relevant to airport operators who must now address emerging concerns about soot, hazardous air pollutants, and $PM_{2.5}$, particularly among the old, very young, and infirm.

Consequently, local population density, distribution and composition were considered. Population density (i.e., population per square mile) for cities with 100,000 or more people were determined based on available data (Census, 2000). These data were used to gauge the potential significance of the population exposures to airport-related $PM_{2.5}$. The data also include the FAA Region, latitude and longitude, and elevation of the evaluated airports.

$PM_{2.5}$ Ambient Monitoring Data

State and local environmental agencies conduct air quality monitoring in their jurisdictions on a regular and continuous basis. These monitors are typically designed to determine regional air pollution conditions while a select number are designed to measure ambient background conditions or specific air pollution sources.

For example, the distances from several airports to nearest air monitoring stations are as follows:

- Hartsfield-Jackson Atlanta International Airport – 3.0 miles
- San Diego International Airport – 2.7 miles
- Philadelphia International Airport – 4.0 miles
- Manchester-Boston Regional Airport – 5.0 miles
- Las Vegas McCarran International Airport – 57 miles

Airport-specific $PM_{2.5}$ air monitoring campaigns have also been carried out at several U.S. airports. The following provides a summary of the available ambient monitoring studies at these airports, at the time of writing.

- **Boston Logan International Airport** – Massport is undertaking a two year air quality monitoring program at the airport. Initiated in 2007 and to be completed in late 2011, the program is intended to evaluate the effects (if any) of a new center-field taxiway on air quality (including $PM_{2.5}$) in the adjoining neighborhoods.
- **Los Angeles International Airport** – since 2000, numerous air monitoring studies have been conducted around the airport in an effort to assess the air quality impacts (including $PM_{2.5}$) of airport operations on surrounding neighborhoods, as well as the impacts of other emission sources in the same area (i.e., surface roadways and stationary sources).
- **Provident T.F. Green Airport** – from 2006 to 2007, the Rhode Island Department of Environmental Management (RI DEM) conducted an air quality monitoring program in the vicinity of the airport. Measurements of $PM_{2.5}$, ultra-fine particulate matter, various organic compounds and meteorological data were collected.

APPENDIX C: CASE STUDY ALTERNATIVE FUELS

This Appendix discusses each of the criteria used to assess the alternative fuels described in Chapter 4. Table 11, which follows the discussions of the criterion at the end of this Appendix, presents the detailed assessment of each fuel and source combination and supports the selection of the final case study alternative fuels, as described in Chapter 4. When a particular airport is assessing whether a particular alternative fuel should be taken forward, they should not necessarily use the weightings used in the ACRP 02-23 project. Instead, they should consider their own business priorities to determine the most appropriate weightings for their own context. The "pre-weighted" information is provided for airports' use at the end of this Appendix, and separately in the Guidance Document.

CHANGE IN $PM_{2.5}$ EMISSIONS

This is the most important criterion and was classed as high priority, with a weighting of 45%. The decrease in emissions was taken from the sources cited.

Jet-fueled Aircraft

The primary domestic fuel used in commercial aircraft turbine engines is Jet-A (ASTM D1655), a fuel derived from oil. Jet A-1 is the international standard for commercial jet fuel and JP-8 is the U.S. military's jet fuel—both are derived from oil. To be adopted, any alternative jet fuel that is developed must meet all of the specifications of jet fuel standards (e.g., freezing point, viscosity, flash point, density and sulfur content). The International Air Transport Association's (IATA) *Fact Sheet on Alternative Fuels (*IATA, 2010) summarizes the requirements of jet fuel as having a freezing point below -40°C for Jet-A and -47°C for Jet A-1, not forming deposits in the engine in high-temperature locations and having an energy content of at least 42.8 MJ/kg.

The two major categories of alternative jet fuels are alternative fossil fuels and biomass fuels. Examples of alternative jet fuels derived from fossil fuels include Fischer-Tropsch (FT) derived gas-to-liquid (GTL) and coal-to-liquid (CTL) fuels. Examples of biomass fuels derived using either FT or hydroprocessed renewable jet (HRJ) fuel processes include fuels derived from animal fats or plants such as sorghum, switchgrass, and camelina. ASTM International has approved an alternative jet fuel specification in annexes to ASTM D7566 for FT and HRJ fuels blended with at least 50% conventional jet fuel.

In published literature, measurements for particulate matter emissions for engines are often recorded using inconsistent metrics by which to establish "thrust" setting and conversions to standard day (standard temperature and pressure) are not always stated. This creates difficulty when analyzing the results and comparing them with, for example, the emission estimates produced by the Federal Aviation Administration's (FAA) Emissions and Dispersion Modeling System (EDMS) during a standard landing and takeoff (LTO) cycle (specified thrust settings as prescribed by the International Civil Aviation Organization (ICAO) Annex 16, Volume II, Aircraft Engines Emissions). To address this difficulty, the ACRP 02-23 project has grouped results from different studies as either low power/thrust (i.e., up to 50% thrust) or high power/thrust (i.e., over 50% thrust). This allows the relative changes in emissions (between standard fuel and an alternative fuel) at low and high thrust to be separately quantified, while still allowing some comparability with EDMS (i.e., taxi and approach would be classed as low thrust, and takeoff and climb as high thrust).

In addition, to quantify primary and secondary particulate matter emissions separately, it is necessary to have data not just on the changes in black carbon mass (g/kg) for estimating primary emissions, but also on sulfur and hydrocarbon (HC) emissions. This enables secondary emissions to be approximated by applying the relative change to the related secondary emissions components estimated for the base case.

The main data that were available for the ACRP 02-23 project have been derived from the Alternative Aviation Fuel Experiment (AAFEX) tests conducted in 2009 at Palmdale, California (Beyersdorf and Anderson, 2009 and Bulzan et al., 2010). Emission indices were available for JP-8, FT GTL, FT CTL, 50/50 JP-8 with FT GTL and 50/50 JP-8 with FT CTL for the CFM56-2C1 engine (i.e., a jet engine). The results of these studies generally indicate that a high reduction in emissions of particulate matter (primary emissions) is possible for neat FT fuels and medium reductions for 50/50 blends. Since neat FT fuel is reported as containing no sulfur, the sulfur emissions are assumed to be negligible and are reported to be below the range of detection by experiments conducted (Cheng, 2009; Corporan, 2007). No renewables data were available at the time of writing in a suitable format. However, as FT and HRJ fuels have similar structures, it is likely that the relative changes in emissions will be of a similar order of magnitude.

Additionally, as the FOA3a equation discussed in Chapter 5 and Appendix A is used to derive particulate matter emissions, it is feasible, in theory, to reduce the sulfur content in the equation and thereby derive a relative-change emission factor for particulate matter for low-sulfur fuels.

Turboprop and Turboshaft Aircraft

The existing data discussed above are related to jet engines and, therefore, are not directly applicable to turboprop and turboshaft engine aircraft, given that they burn fuels differently. A few studies have been undertaken for turboshaft aircraft (Corporan and Cheng, 2010, Corporan et al., 2007, Cheng, 2009) that consider emissions of particulate matter for JP-8 and FT GTL. The results from these studies indicate a high particulate matter emission reduction for neat FT fuels and medium reductions for 50/50 blends compared with standard fuel. However, EDMS does not calculate particulate matter emissions for turboprop and turboshaft aircraft, and turboprop and turboshaft aircraft emissions were calculated as part of the sensitivity study only (refer to Chapters 5 and 6 and to Appendices D and E). Therefore FT GTL was considered on an emissions only basis as part of the sensitivity analysis for turboprop and turboshaft aircraft.

Auxiliary Power Units (APUs)

Very few data exist for APUs. The data that do exist (Bulzan et al., 2010) suggest that the changes in emissions are similar to those that occur for aircraft main engines at “high” thrust.

AvGas Aircraft

Appendix A discussed the limitations of EDMS with regard to its lack of inclusion of particulate matter emission data for piston-engine aircraft. A separate sensitivity analysis was undertaken to estimate the potential additional emissions from piston-engine aircraft using 100LL and the potential emissions reductions from 91/96UL. The emission estimates for both 100LL and 91/96UL were taken from limited data published by the Swiss Federal Office of Civil Aviation (FOCA, 2007b), which suggested soot emission factors for piston-engine aircraft (all in the

2.5 µm range) as reproduced in Table 8 in Appendix A. These data depict a high reduction in particulate matter emissions.

It should be noted that few piston-engine aircraft are certified to run on unleaded fuel in the U.S. (although, technically, 91/96 UL AvGas grade is not completely unleaded) and there is limited availability.

Ground Support Equipment (GSE)

GSE tends to run primarily on diesel. However, as noted in Appendix A, there are a number of alternative-fueled equivalent models, many of which are incorporated in EDMS. These include electric, liquefied propane gas (LPG), and compressed natural gas (CNG). Not all GSE models have a relevant alternative-fueled counterpart in EDMS or generally available, so only those models with an alternative fuel equivalent were used in the ACRP 02-23 project.

In terms of the alternative fuels, electric has zero particulate matter direct emissions. Relative to gasoline, LPG results in a small reduction of $PM_{2.5}$, while CNG performs slightly better than LPG. Diesel GSE produces the highest particulate matter emissions, typically having an emission factor more than ten times greater than that for 4-stroke gasoline engines. Therefore, replacing the fuel used in GSE from diesel to LPG or CNG will produce much higher particulate matter emissions savings compared with replacing gasoline GSE.

The sulfur content of fuel contributes a relatively small proportion of the total particulate matter emission formation. Therefore, low-sulfur diesel is likely to have little impact on particulate matter emissions compared with standard diesel. In addition, the legal limit of sulfur content in off-road fuel is being lowered in the future, which means that any gains of using low-sulfur diesel in GSE would only be short-term as the industry moves towards low-sulfur diesel anyway. Particulate matter emission reductions for ethanol in the ACRP 02-23 project are based on a previous literature review of data for road vehicles (AEA, 2008). Low percentage ethanol blends (up to about E10) can be used in gasoline-fueled GSE. Higher blends require some limited conversion of the vehicle, which may invalidate the vehicle's warranty. For ethanol, limited data were found to be available with E5 and E15 data derived by scaling the relative change for E10 data. The approach for E85 used a worst case approach (i.e., the E5 scaled results), resulting in E85 appearing to have little impact on particulate matter emissions compared with E10.

Similarly, low percentage biodiesel blends (such as B5) may be used in diesel-fueled GSE without significant equipment concerns. Higher-percentage blends may invalidate the equipment's warranty as discussed below under Road Vehicles.

The U.S. Environmental Protection Agency (EPA) (2002) particulate matter emission reductions for road vehicles are estimated at around 6% for B10, 12% for B20 and 47% for B100. Assuming these percentages can be applied to GSE, they are smaller reductions compared with replacing diesel GSE with gasoline, LPG or CNG (where the reduction could be between 90% and 95%). In addition to changes in particulate matter emissions, practical limitations may become an issue such as higher-biodiesel blends gelling, depending on feedstock, in cold weather. Similarly, a biocide may need to be added to higher-percentage blends to prevent microbial growth and subsequent blocking of fuel filters.

Road Vehicles

Smaller road vehicles tend to run on gasoline and larger vehicles (e.g., trucks) on diesel. In terms of alternative fuels, electric road vehicles produce zero particulate matter direct emissions. The MOBILE model, which EDMS uses, incorporates emission factors for "natural gas" road vehicles as the equivalent "catch-all" for liquefied natural gas (LNG) and CNG. These emission factors can be used to generate emissions for "natural gas" for calculations prior to the 2004 model year. For MOBILE calculations after 2004, the MOBILE "natural gas" emission factors are actually higher than the corresponding emission factors for Tier 2 gasoline vehicles, which are unlikely to be realistic and, therefore, add uncertainty to these emission factors.

As noted for GSE, CNG has negligibly less particulate matter emissions relative to gasoline and, therefore, replacing gasoline vehicles will have little impact. However, benefits would be seen by replacing diesel vehicles with those running on gasoline or "natural gas."

Finally, low-sulfur road diesel is already in use in the U.S. and, therefore, this cannot be classed as an alternative fuel.

AVAILABILITY OF FUEL

This criterion reflects the current availability of the alternative fuel. In time, this will change, especially with regard to aviation fuels, where many are only at the certification stage and not yet commercially produced. Electricity, LPG, CNG, low percentage ethanol and biodiesel blends are readily available in many U.S. states and are, therefore, classed as "high" in terms of fuel availability. Higher-percentage blends of ethanol and biodiesel should only be used in converted or new vehicles and, as such, the level of demand for these fuels is lower. Therefore, availability is more limited. As older vehicles are replaced with newer ones, where manufacturers have tested alternative fuels, demand and availability can be expected to increase. This criterion was classed as low priority with a weighting of 5%.

AVAILABILITY OF NEW VEHICLES

This criterion reflects the current availability of new vehicles that can use the alternative fuel in question. Again, new models will be developed over time and vehicles specifically designed for alternative fuels will become cheaper and more widespread. As discussed above, for GSE there are limitations in terms of availability and applicability – only low power electric GSE (i.e., small push-back tugs as oppose to large push-back tugs) are currently available. This criterion was classed as low priority with a weighting of 5%.

COST TO CONVERT EXISTING VEHICLES

In many instances, it is more cost-effective to convert an existing vehicle to run on a new or modified fuel (e.g., high-percentage blends of ethanol and biodiesel) compared with the cost of buying new – unless replacement is already under consideration for other reasons. Therefore, the cost to convert vehicles has been included as a criterion so that it can be compared against costs for new vehicles. This criterion has been classed as low priority as different airports and airside operators will have different priorities and these costs will change in future years. It has a weighting of 5%.

DROP-IN FUEL FOR EXISTING VEHICLES

If the fuel is a drop-in fuel where no new vehicles or modifications are necessary, then the only cost involved is likely to be in terms of additional fuel costs and infrastructure. Therefore, this is an important consideration. It should be noted that all aircraft fuels considered are drop-in fuels. This criterion has been classed as low priority as different airports, and airside operators will have different priorities. It has a weighting of 5%.

GREENHOUSE GAS (GHG) LIFE-CYCLE EMISSIONS

GHG life-cycle emissions can be difficult to quantify because they require consideration of the emissions incorporated in extraction, processing, and transmission processes as well as emissions associated with burning the fuel, sometimes referred to as “well to wheel.” Some “green” fuels, such as biodiesel, have higher upstream emissions and are, therefore, classed as having GHGs almost comparable to conventional fuels, unless high-percentage blends are used. In terms of electricity, the method used to generate the electricity can be highly variable from airport to airport and, therefore, electricity has been classed as variable. In terms of aviation biofuels, as most certified or near-certification fuels are around a 50% blend, the emissions may be comparable to conventional fuels in a similar manner to that of biodiesel. It is only when high-percentage blends are used that real savings are seen. This criterion was classed as low priority, with a weighting of 5%.

EMISSION DATA SOURCE RELIABILITY

This category relates to the emission data that are available for assessing the changes in particulate matter emissions. U.S. government and academic peer reviewed data are classed as high-quality data, especially if they are widely accepted and have been verified by similar studies across the world with similar results. Some government and academic peer reviewed literature relate to a limited sample such as one aircraft engine type and, therefore, are classed as medium quality data. Other data are classed as low quality because they are not specific to the source (e.g., relative changes for road vehicles applied to GSE) even though the original data may have been medium or high quality. Where no appropriate data are available, this column is classed as “N/A” (not applicable). The weighting of this criterion was classed as medium priority because it was considered to be more important than other criteria, but still less significant than the primary criterion being considered, “Change in $PM_{2.5}$ Emissions.” It has a weighting of 10%.

FUEL COST RELATIVE TO CONVENTIONAL

This criterion reflects the current price of fuel relative to conventional fuel and is mainly based on the U.S. DOE fuel prices report (U.S. DOE, 2011). It should be noted that this will change over time, especially with regard to aviation fuels, where many are only at the certification stage and not commercially produced and are, therefore, relatively expensive. CNG, low percentage ethanol and biodiesel blends are readily available in many states and are, therefore, not excessively expensive. However, higher-percentage blends of ethanol and biodiesel have limited current commercial use and are, therefore, more expensive. In general, as demand for alternative fuels increases, it is likely that prices will decrease. This criterion was classed as low priority, with a weighting of 5%.

VEHICLE COST COMPARED WITH CONVENTIONAL

The current availability of some alternative-fueled vehicles is limited and, therefore, the cost of these vehicles is often high compared with standard vehicles of the same type. However, other conventional vehicles are now being manufactured to allow the use of higher-percentage blends of ethanol and biodiesel (sometimes called “flex-fuel” vehicles). Therefore, the price of ethanol and biodiesel compatible vehicles is not particularly high compared with other vehicles. Electric vehicles are relatively expensive, primarily due to the cost of batteries. As demand for alternative-fueled vehicles increases, prices are likely to reduce. This criterion was classed as low priority, with a weighting of 5%.

ADDITIONAL INFRASTRUCTURE NEEDED

This criterion allows for some consideration of the need for additional infrastructure. It is assumed that there is an existing, nearby supply of electricity, diesel, gasoline, and standard aviation fuel as appropriate. For drop-in fuels, additional infrastructure would be limited to additional storage tanks and fueling facilities. For CNG and LPG, more specialized equipment would be needed.

LPG is a gas at normal temperature and pressure, but liquefies at pressures of around 10 atmospheres at 38°C (dependent on its exact composition). Hence, refueling involves pumping a liquid under pressure in a pressurized system. This requires more complex equipment than is required when filling a vehicle with gasoline or diesel.

CNG is a compressed gas and will not liquefy above -82°C. Hence, refueling involves moving a highly compressed gas, typically at a pressure of around 300 atmospheres, from a high pressure storage tank. Often, CNG is delivered by a low pressure grid. Therefore, a compressor to pump the CNG into the tank and equipment to dry it are also required. This requires specialist refueling equipment that is quite different to that used for liquid hydrocarbons (HCs). An alternative refueling method is the natural gas equivalent of electrical trickle charging, where gas is slowly pumped into the vehicle (e.g., overnight). This does not require the high pressure storage tank, as gas can be supplied directly from the compressor.

Recharging electric vehicles, assuming that trickle charging can be used and spare capacity already exists, requires little infrastructure development. However, issues may arise from parking vehicles and equipment for long periods and with further capacity potentially being required. Gate electricity and pre-conditioned air supply for reducing APU use are likely to require more infrastructure development than vehicle recharging points.

Alternative AvGas will need separate tanks and fueling as not all piston-engine aircraft can use alternative blends.

This criterion has been classed as low priority as different airports and airside operators will need to consider infrastructure differently. It has a weighting of 5%.

WARRANTY VALIDITY ISSUE

Some fuels, such as high-percentage blends of biodiesel, may be used in existing vehicles without modification, but may invalidate the vehicle's warranty. This is an issue that vehicle owners will need to consider where warranties are still in date. Similarly, retrofitting existing vehicles for LPG or CNG use is likely to invalidate the warranty. This criterion has been classed as low priority as different airports and airside operators will have different priorities. It has a weighting of 5%.

Table 11 – Alternative Fuel Matrix

Criterion	**Change $PM_{2.5}$ emissions (H, M, L)**	**Availability of fuel (H, M, L)**	**Availability of new vehicles (H, M, L)**	**Cost to convert existing vehicles (H,M,L)**	**Drop-in fuel for existing vehicle? (Y/N or N/A)**	**GHG life-cycle emissions (H, M, L)**	**Emission data source reliability (H, M, L)**	**Cost of fuel compared with conventional (H, E, L)**	**Cost of vehicles compared with conventional (H, M, L)**	**Additional infrastructure needed (H, M, L)**	**Warranty validity issue (Y/N or N/A)**
Low-sulfur Jet-A for aircraft	L	L	H	N/A	Y	H	L	E	N/A	L	N
FT (natural gas) aircraft	**M**	**L**	**H**	**N/A**	**Y**	**H**	**M**	**H**	**N/A**	**L**	**N**
FT (coal) aircraft	**M**	**L**	**H**	**N/A**	**Y**	**H**	**M**	**H**	**N/A**	**L**	**N**
FT (biomass) aircraft	M	L	H	N/A	Y	H	L	H	N/A	L	N
HRJ (biomass) aircraft	M	L	H	N/A	Y	H	L	H	N/A	L	N
91/96UL AvGas for piston-engine aircraft	**H**	**L**	**L**	**L**	**Y**	**H**	**M**	**E**	**N/A**	**M**	**Y**
FT (natural gas) APU	**M**	**L**	**H**	**N/A**	**Y**	**H**	**L**	**H**	**N/A**	**L**	**N**
FT (coal) APU	**M**	**L**	**H**	**N/A**	**Y**	**H**	**M**	**H**	**N/A**	**L**	**N**
FT (biomass) APU	M	L	H	N/A	Y	H	L	H	N/A	L	N
HRJ (biomass) APU	M	L	H	N/A	Y	H	L	H	N/A	L	Y
Low-sulfur Jet-A for APU	L	L	H	L	Y	H	L	E	N/A	L	N
Electricity to replace some APU use	**M**	**H**	**H**	**N/A**	**Y**	**V**	**H**	**V**	**N/A**	**H**	**N**
Electric GSE	**H**	**H**	**H**	**N/A**	**N**	**V**	**H**	**V**	**H**	**L**	**N**
LPG GSE replacing gasoline GSE	L	H	L	L	N	H	H	H	M	M	Y
LPG GSE replacing diesel GSE	**H**	**H**	**L**	**H**	**N**	**H**	**H**	**H**	**M**	**M**	**Y**
CNG GSE replacing gasoline GSE	**M**	**H**	**L**	**M**	**N**	**H**	**H**	**L**	**M**	**H**	**Y**
CNG GSE replacing diesel GSE	**H**	**H**	**L**	**H**	**N**	**H**	**H**	**L**	**M**	**H**	**Y**

Criterion	**Change $PM_{2.5}$ emissions (H, M, L)**	**Availability of fuel (H, M, L)**	**Availability of new vehicles (H, M, L)**	**Cost to convert existing vehicles (H,M,L)**	**Drop-in fuel for existing vehicle? (Y/N or N/A)**	**GHG life-cycle emissions (H, M, L)**	**Emission data source reliability (H, M, L)**	**Cost of fuel compared with conventional (H, E, L)**	**Cost of vehicles compared with conventional (H, M, L)**	**Additional infrastructure needed (H, M, L)**	**Warranty validity issue (Y/N or N/A)**
Low-sulfur diesel GSE	L	H	H	N/A	Y	H	L	E	N/A	L	N
E5 in gasoline-fueled GSE	L	H	M	N/A	Y	H	L	E	N/A	N/A	N
E10 in gasoline-fueled GSE	**M**	**H**	**M**	**N/A**	**Y**	**H**	**L**	**E**	**N/A**	**N/A**	**N**
E15 in gasoline-fueled GSE	M	L	L	L	N	H	L	N/A	L	L	Y
E85 in gasoline-fueled GSE	L	M	L	L	N	M	L	H	L	L	Y
B5 in diesel-fueled GSE	L	H	H	N/A	Y	H	L	E	N/A	N/A	N
B10 in diesel-fueled GSE	L	L	M	L	N	H	L	N/A	L	M	Y
B15 in diesel-fueled GSE	L	L	M	L	N	H	L	N/A	L	M	Y
B20 in diesel-fueled GSE	**L**	**M**	**M**	**L**	**N**	**H**	**L**	**E**	**L**	**L**	**Y**
B100 in diesel-fueled GSE	**M**	**M**	**L**	**M**	**N**	**M**	**L**	**H**	**L**	**L**	**Y**
Low-sulfur diesel road vehicles	N/A	N/A	N/A	N/A	Y	N/A	N/A	E	N/A	N/A	N
Natural gas road vehicles to replace diesel	**H**	**H**	**M**	**M**	**N**	**H**	**L**	**L**	**M**	**H**	**N**
Electric road vehicles	**H**	**H**	**L**	**N/A**	**N**	**V**	**H**	**V**	**H**	**L**	**N**
E5 in gasoline-fueled road vehicles	L	H	H	N/A	Y	H	L	E	N/A	N/A	N
E10 in gasoline-fueled road vehicles	M	H	H	N/A	Y	H	M	E	N/A	N/A	N
E15 in gasoline-fueled road vehicles	M	L	H	L	N	H	L	N/A	L	L	Y
E85 in gasoline-fueled road vehicles	L	M	H	L	N	M	L	H	L	L	Y
B5 in diesel-fueled road vehicles	L	H	H	N/A	Y	H	H	E	N/A	N/A	N
B10 in diesel-fueled road vehicles	L	L	H	L	N	H	H	N/A	N/A	M	Y
B15 in diesel-fueled road vehicles	L	L	H	L	N	H	H	N/A	N/A	M	Y
B20 in diesel-fueled road vehicles	**L**	**M**	**H**	**L**	**N**	**H**	**H**	**E**	**N/A**	**L**	**Y**

Criterion	**Change PM$_{2.5}$ emissions (H, M, L)**	**Availability of fuel (H, M, L)**	**Availability of new vehicles (H, M, L)**	**Cost to convert existing vehicles (H,M,L)**	**Drop-in fuel for existing vehicle? (Y/N or N/A)**	**GHG life-cycle emissions (H, M, L)**	**Emission data source reliability (H, M, L)**	**Cost of fuel compared with conventional (H, E, L)**	**Cost of vehicles compared with conventional (H, M, L)**	**Additional infrastructure needed (H, M, L)**	**Warranty validity issue (Y/N or N/A)**
B100 in diesel-fueled road vehicles	**M**	**M**	**L**	**M**	**N**	**M**	**H**	**H**	**M**	**L**	**Y**

Note: Bold denotes the fuel/source combinations assessed

APPENDIX D: DETAILED METHODOLOGY

Chapter 5 describes how the data for the base case and alternative fuel scenarios were generated. This appendix provides further details on the methodology.

EMISSIONS INVENTORY FOR BASE CASE

The Emissions and Dispersion Modeling System (EDMS) input data, as shown in Table 12, were obtained and organized from a variety of sources including the airport owner/operator, the airport tenants, and the Federal Aviation Administration's (FAA) databases. This information includes aircraft activity levels, and ground support equipment (GSE) and auxiliary power unit (APU) use, road vehicle, and stationary source characteristics. Appendix A of the EDMS user manual (U.S. FAA, 2009a) provides an overview and screen shots of the data needed to compile an inventory and how to enter it into EDMS.

Table 12 – Data Used in $PM_{2.5}$ Emissions Inventories

Source Category	Data
Aircraft	LTO by aircraft type and engine type Taxi-in, taxi-out, delay times (aircraft time in mode) Profiles of quarter hour, daily and monthly activity levels Runway and taxiway assignments and coordinates Terminal/gate assignments and locations
Ground support equipment (GSE)	Number and type by aircraft type Fuel type Size and load Operating times
Auxiliary power units (APU)	Percent of gates with fixed power units Percent of gates with fixed pre-conditioned air
Road vehicles	Location by segment Vehicle fleet mix by segment Roadway traffic volume by segment Average speed Emission factors (generated using either MOBILE6.2 or EMFAC2007 models)
Parking facility	Location by parking lot Vehicle fleet mix by parking lot Traffic volume by parking lot Travel distance Idle time
Stationary sources	Type and location Fuel type and quantity Stack height and diameter Exhaust temperature and velocity

First-Order Approximation (FOA) 3a Methodology

The FOA3a methodology accounts for the volatile and non-volatile components of emissions of fine particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$), where the fuel sulfur content, fuel-based organics, and lubricating oil contribute to volatile $PM_{2.5}$. Data on the size distribution of aircraft exhaust particulate matter indicates that virtually all of the mass is associated with $PM_{2.5}$.

As indicated in Chapter 5, to determine the volatile $PM_{2.5}$ emissions for jet engines, for each mode within the LTO cycle, the following equation was derived from the simplified version of the FOA3a function for each aircraft:

$$PM_{sec} = (0.0085 \text{ x } HC) + (3 \text{ x } 1{,}000 \text{ x } FSC \text{ x } \varepsilon \text{ x } F) + (1.4 \text{ x } LTO)$$

Where:
PM_{sec} = Volatile particulate matter from aircraft engines (grams)
HC = Total hydrocarbon emissions from aircraft engines (grams)
FSC = Fuel sulfur content, 0.00068 (assume majority is Jet-A)
ε = 0.05 (assume FOA3a)
F = Total fuel consumption from aircraft engines (kg)
LTO = Total number of landing and takeoff (LTO) cycles for aircraft

Note that the term 1.4 x LTO is jointly applicable to the takeoff and climb modes.

For the alternative fuels, the above three components (i.e., $PM_{2.5}$ related to hydrocarbon (HC), sulfur and lubricating oil (1.4 x LTO)), in addition to the non-volatile component, have been separately scaled, based on the anticipated change in non-volatile emissions, fuel sulfur content, and HC emissions.

EMISSIONS INVENTORY FOR ALTERNATIVE FUEL SCENARIOS

Ratio of Scenario Source Type Emissions to Base Case

The ratio of emissions of the alternative fuel versus the base fuel for each relevant source and fuel type were used to scale the base case emissions to the alternative fuel scenario emissions as outlined in Table 13, Table 14 and Table 15. Sources of information for the alternative fuel emission factors for each of these source types are discussed in Chapters 2, 4, and 5 and in Appendix A and Appendix C. They are also outlined in Table 13, Table 14, and Table 15.

Table 13 – Alternative Fuel Emission Factors (AF) Ratios for Jet Turbines and Turbofan Aircraft (main engines and APU)

Fuel and Source type	Source	Ratio (AF)
FT (natural gas) jet aircraft main engines high thrust non-volatile emissions	Derived from black carbon emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine, NASA report on AAFEX (Anderson et al., 2011)	0.41
FT (natural gas) jet aircraft main engines all thrust sulfur emissions	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	0.50
FT (natural gas) jet aircraft main engines high thrust volatile emissions	Derived from HC emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (Bulzan et al., 2010)	1.00
FT (natural gas) jet aircraft main engines low thrust non-volatile emissions	Derived from black carbon emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine, NASA report on AAFEX (Anderson et al., Feb 2011)	0.41
FT (natural gas) jet aircraft main engines low thrust volatile emissions	Derived from hydrocarbon emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (Bulzan et al., 2010)	1.00
FT (coal) jet aircraft main engines high thrust non-volatile emissions	Derived from black carbon emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine, NASA report on AAFEX (Anderson et al., 2011)	0.59
FT (coal) jet aircraft main engines all thrust sulfur emissions	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	0.50
FT (coal) jet aircraft main engines high thrust volatile emissions	Derived from HC emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (Bulzan et al., 2010)	1.00
FT (coal) jet aircraft main engines low thrust non-volatile emissions	Derived from black carbon emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine, NASA report on AAFEX (Anderson et al., 2011)	0.53
FT (coal) jet aircraft main engines low thrust volatile emissions	Derived from HC emissions for 50/50 blend and JP-8 in a high-bypass turbofan engine (Bulzan et al., 2010)	1.00
FT (coal) APU	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 (Anderson et al., 2011)	0.56
FT (natural gas) APU	Assumed as per FT (coal) APU non-volatile emissions above	0.56
Electricity to replace some APU use	Assumes all APU run for 7 minutes based on EDMS defaults and FAA guidance (2010) for APU use when the availability of pre-conditioned air and gate power is available	Ratio based on 7 minutes/base case time

Note: aircraft high thrust is defined as takeoff and climb, and low thrust as idle and approach.

For jet turbines and turbofan engine aircraft, the factors were derived from experiments on one type of high-bypass turbofan and one APU. The NASA Alternative Aviation Fuel Experiment (AAFEX) report (Anderson et al., 2011) was the primary source for the main engine and APU data. A more recent PARTNER report (Lobo, 2011), of APU alternative fuel emissions was published too late to be incorporated in the ACRP 02-23 project. Further study is needed to understand the variation that the use of these alternative fuels could have on other types of turbine engine.

Table 14 – Alternative Fuel Emission Factors (AF) Ratios for other Aircraft Types

Fuel and Source type	Source	Ratio (AF)
91/96UL AvGas for piston-engine aircraft approach	Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (FOCA, 2007a)	0.025
91/96UL AvGas for piston-engine aircraft idle	Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (FOCA, 2007a)	0.020
91/96UL AvGas for piston-engine aircraft takeoff	Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (FOCA, 2007a)	0.030
91/96UL AvGas for piston-engine aircraft climb	Derived from 91/96UL and 100LL emission factors in Swiss Federal Office of Civil Aviation (FOCA, 2007a)	0.029
FT (natural gas) Turboprop and turboshaft aircraft high thrust non-volatile emissions	Derived from black carbon emissions for 50/50 blend and JP-8 in small turboshaft engine (Corporan et al., 2007)	0.46
FT (natural gas) Turboprop and turboshaft aircraft low thrust non-volatile emissions	Derived from black carbon emissions for 50/50 blend and JP-8 in small turboshaft engine (Corporan et al., 2007)	0.53

Note: aircraft high thrust is defined as takeoff and climb, and low thrust as idle and approach.

The data in Table 14 have only been used as an extension to the sensitivity analysis described in Chapter 5.

Table 15 – Alternative Fuel Emission Factors (AF) Ratios for GSE and Road Vehicles

Fuel and Source type	Source	Ratio (AF)
Electric GSE	Used EDMS database files to replace GSE with electric equivalent where available	Emissions recalculated using EDMS databases
LPG GSE replacing diesel GSE	Used EDMS database files to replace diesel GSE with LPG equivalent where available	Emissions recalculated using EDMS databases
CNG GSE replacing gasoline GSE	Used EDMS database files to replace gasoline GSE with CNG equivalent where available	Emissions recalculated using EDMS databases
CNG GSE replacing diesel GSE	Used EDMS database files to replace diesel GSE with CNG equivalent where available	Emissions recalculated using EDMS databases
E10 in gasoline-fueled GSE	Based on E10 factor in AEA (2008) for road vehicles	0.6
B20 in diesel-fueled GSE	Based on U.S. EPA (2002) exponential equation for biodiesel for road vehicles	0.880
B100 in diesel-fueled GSE	Based on U.S. EPA (2002) exponential equation for biodiesel for road vehicles	0.528
Natural gas road vehicles to replace diesel	Based on running MOBILE with 100% natural gas for each airport	Emissions recalculated using MOBILE
Electric road vehicles	Electricity use has no direct PM$_{2.5}$ emissions	0
E10 in gasoline-fueled road vehicles	Based on E10 factor in AEA (2008) for road vehicles	0.6
B20 in diesel-fueled road vehicles	Based on U.S. EPA (2002) exponential equation for biodiesel for road vehicles	0.880
B100 in diesel-fueled road vehicles	Based on U.S. EPA (2002) exponential equation for biodiesel for road vehicles	0.528

Note that as shown in Table 15, for some fuel and source combinations, the alternative emissions have been calculated using EDMS databases (e.g., GSE) or MOBILE6.2 (e.g., for road vehicles), rather than using a specific ratio (AF).

Alternative Fuel Penetration

For those sources that are not considered to be a drop-in fuel, the following penetration factors shown in Table 16 were used.

Table 16 – Penetration Factor (P)

Fuel and Source type	Source and Assumption	Penetration Factor (P)
E10 in gasoline-fueled GSE	This is a drop-in fuel and, while not all airports will provide it, it is assumed that those that do will be unlikely to have multiple fuels available. Therefore, 100% of the fleet operating at these airports would be refueling on the drop-in fuel	1
B20 in diesel-fueled GSE	This is a drop-in fuel and, while not all airports will provide it, it is assumed that those that do will be unlikely to have multiple fuels available. Therefore, 100% of the fleet operating at these airports would be refueling on the drop-in fuel	1
B100 in diesel-fueled GSE	This is not classed as a drop-in fuel and, as such, would need either specialist equipment or some engine modifications (though these may be fairly small), which may invalidate the warranty. While it is feasible that all diesel GSE could be modified to use B100, it is unlikely, therefore, two penetration factors have been used	1
		0.5
Natural gas road vehicles to replace diesel	In the U.S. airport sector, natural gas accounts for about 9% of total vehicular use (Natural Gas Vehicles for America, 2011)	0.09
	Resources for the Future (2010) cites a higher scenario of 32% of the heavy-duty truck fleet fueled by natural gas in 2020	0.32
Electric road vehicles	Electric Power Research Institute (EPRI, 2007) developed a scenario that, in 2020, plug-in electric hybrid vehicles will cover about 10% of light vehicle miles, with 5% of vehicle miles using electricity only. Therefore, both 10% and 5% have been used.	0.1
		0.05
E10 in gasoline-fueled road vehicles	U.S. EIA AEO,2011 (p84)	1
B20 in diesel-fueled road vehicles	In U.S. EIA AEO, 2011 (Table 11) the ratio of biodiesel to diesel was 0.026. Assume all biodiesel is used in B20, result is 0.128 (i.e., 0.026/0.2)	0.128
	U.S. EIA AEO, 2011 (p11): Based on California's Low Carbon Fuel Standard	1
B100 in diesel-fueled road vehicles	In U.S. EIA AEO, 2011 (Table 11) the ratio of biodiesel to diesel was 0.026. Assume all B100.	0.026
	Biodiesel potential from soya beans (Hill et al., 2006)	0.06

ATMOSPHERIC DISPERSION MODELING ANALYSIS

General EDMS and AERMOD Control Options

Default EDMS aircraft engine assignments, where necessary, were based on worldwide or U.S. designations, depending on the geographic domain serviced by each case study airport. For example, Hartsfield-Jackson Atlanta International Airport (ATL) used worldwide defaults, while Manchester-Boston Regional Airport (MHT) used U.S. defaults based on the service area of the airports. The determination of aircraft $PM_{2.5}$ emissions and pollutant concentrations used the performance based aircraft times-in-mode with the airfield sequence model (simulation of the movement of aircraft within the airfield).

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 modeled results (i.e., by the sources listed in Table 19 and Table 20) and AERMOD (Version 09292) run outside of EDMS. AERMOD default regulatory options (stack-tip downwash, buoyancy-induced dispersion, and final plume rise), default wind-speed profile categories and default potential temperature gradients were used. No pollutant decay was also assumed.

The selection of the appropriate dispersion coefficients, accounting for terrain and atmospheric interactions in the pollutant plume, depends on the land use within 3 km of the project site. The land use typing for the dispersion analysis was based on the classification method defined by Auer (1978), using pertinent United States Geological Survey (USGS) 1:24,000 scale (7.5 minute) topographic maps of the airport areas. If the Auer land use types of heavy industrial, light-to-moderate industrial, commercial, and compact residential account for 50% or more of the total area, the U.S. Environmental Protection Agency (EPA) *Guideline on Air Quality Models* recommends using urban dispersion coefficients. Otherwise, the appropriate rural coefficients were used. Based on observation of the area surrounding the airport sites, rural dispersion coefficients were applied for each case study airport.

Auxiliary Power Unit (APU) Operating Time

For the base case, if APUs were contained in a particular aircraft, it was assumed that they operated for 26 minutes if pre-conditioned air/gate power units were not available at a particular gate. If pre-conditioned air/power units were available at a particular gate, then APUs were generally assumed to operate based on airport-specific data (about 7 minutes). These values are in line with EDMS defaults and FAA guidance (2010h) for APU use when the availability of pre-conditioned air/gate power is known.

It should be noted that the AERMOD dispersion analysis was performed without incorporating particulate depletion due to gravitational settling, chemical transformation, and wet deposition. These principles are difficult to simulate.

Receptors

A receptor network was developed to capture and adequately define the area of maximum impact. Receptors used in the analysis include a discrete receptor grid and a polar receptor grid.

The discrete receptors generally represent areas where high concentrations of pollutants are anticipated and areas where the general public has access. These receptors typically include terminal curbsides and access areas, public parking facilities near the ends of runways where aircraft are queuing and waiting to takeoff, and nearby parks, schools, and residential areas. The discrete receptor grid is described as:

- **Boundary receptors** – these receptors are located in areas along the airport boundary including runway ends at a spacing of 10° to 15°.
- **Terminal area receptors –** these receptors are located within the main terminal curbside area.
- **Sensitive receptors –** these receptors include schools, parks, residential areas, day-care centers and other public areas located in the vicinity of the airport.

Polar grids were developed to contain 36 radii, spaced at 10°intervals. The inner polar grid extended from 500 to 2,500 meters from the center of the airports at intervals of 500 meters. The outer polar grid extended from 3,000 to 10,000 meters from the emission sources at intervals of 1,000 meters. Any polar grid receptor located on the restricted areas of airport property was discounted. This polar grid approach normalizes the spatial domain around airports of differing sizes and configurations, and it allows for a better comparison of the predicted concentrations at each airport (as the grid is exactly the same at each airport). Polar grid receptors located close to key sources of emissions (e.g., center of gates, taxiways, runways, and roadways) were removed as they would not be representative of public exposure.

Terrain Data

The AERMAP (Version 09040) processor was used to determine receptor elevations for all of the receptors. AERMAP uses digital elevation model (DEM) data to calculate terrain elevations and associated hill heights for use in AERMOD. DEM 1° format data within the vicinity of the airports were used. Receptors are placed at a height of 1.8 meters (typical breathing height) above ground level.

Meteorological Data

Meteorological conditions such as wind speed, wind direction, atmospheric stability, and air temperature were also specifically assessed for each case study airport. These meteorological data were acquired from the National Climatic Data Center (NCDC) and processed using AERMET (Version 06341), the meteorological processor contained within AERMOD. Figure 17 provides the annual wind roses for the meteorological data for the five case study airports and their analysis years. Each airport has a unique set of meteorological conditions related to wind direction, wind speed, ambient temperature, atmospheric stability, and turbulence indices.

The meteorological analysis year was dictated by the emission analysis year for each case study airport. The analysis emission year was dictated by the availability of airport operational data in EDMS format. A summary of the meteorological data for each case study airport is shown in Figure 17. For example, the ATL analysis was based on operational data from a recently completed emissions inventory for 2008, while the MHT analysis was based on a recently completed emissions inventory for 2007. The meteorological data, ambient monitoring data and other year sensitive data were for the same year on a case study airport basis.

The term “atmospheric mixing height” generally describes the height above ground level below which the atmospheric mixing of most air pollutants occurs (and above which little mixing occurs). Within the atmosphere, this height (expressed in meters or feet) is determined by an assortment of environmental factors including air temperature, humidity, solar radiation, wind speed, and topographic features on the ground (e.g., valleys, mountains, vegetative cover, reflective and impervious surfaces, water bodies). The atmospheric mixing height is dynamic and varies both spatially and temporally throughout the day, season and year with corresponding changes in these above mentioned environmental factors.

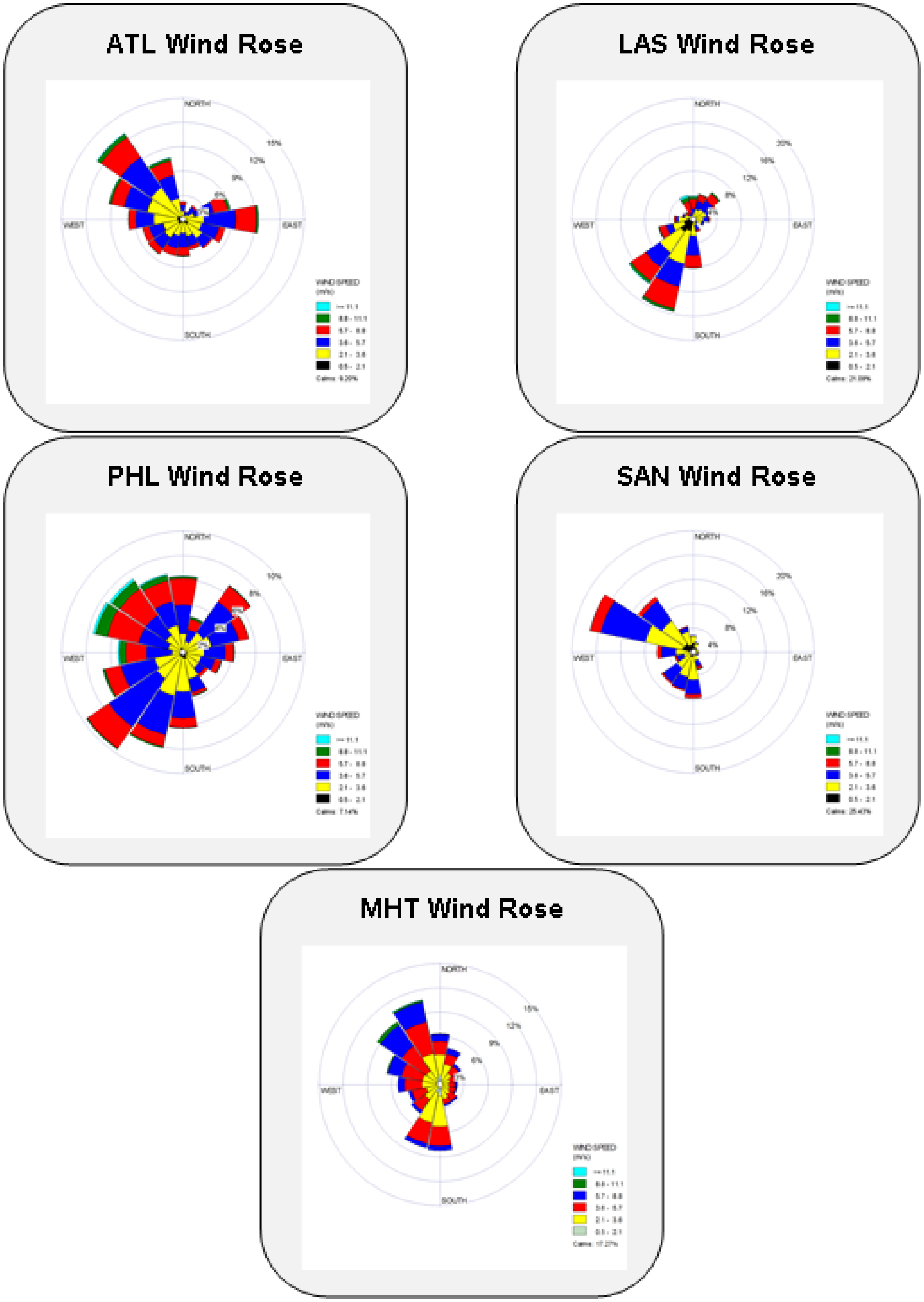


Figure 17 – Wind Roses for Five Case Study Airports

Mixing Height

In air quality assessments (i.e., emissions inventories and dispersion modeling), the atmospheric mixing height is used to define the vertical limits of a particular study area. In simple terms, this is the height of a figurative “box” within which airport-related emissions are assumed to occur and disperse, with the ground representing the bottom and the horizontal distances representing the sides of the box.

As mentioned, the height of the mixing zone varies by time of day and by season. Typically, during summer daylight hours, the mixing height can be 6,500 meters. In winter, the mixing height may be as low as a hundred meters. Table 17 contains the annual average mixing heights for the five case study airports. The mixing height for Las Vegas McCarran International Airport (LAS) is generally higher due to its arid, high-altitude climate.

Table 17 – Atmospheric Mixing Height (meters)

ATL	LAS	MHT	PHL	SAN
811	2,207	661	796	853

To enable direct comparison of the $PM_{2.5}$ emissions between the case study airports, the aircraft emissions reported in Chapter 6 were normalized to 914 meters (3,000 feet) (i.e., the mixing height was set to 914 meters for all case study airports). However, for the dispersion modeling, the original mixing heights were used. This approach was discussed with the FAA and, additionally, is in line with the EPA recommendations and the Airport Cooperative Research Program (ACRP) Report 11 on greenhouse gas (GHG) emissions inventories (ACRP, 2009).

AMBIENT MONITORING DATA

Local and state air protection agencies operate ambient monitoring networks to measure ambient concentrations as a means of assessing public health impacts and National Ambient Air Quality Standards (NAAQS) compliance. For $PM_{2.5}$ concentrations, these ambient monitoring stations typically measure daily values at intervals of three to six days, from which the annual average concentrations are determined.

Monitoring data were obtained from the EPA AirData database for stations within each case study airport’s air quality region. The representative background concentrations were then determined based on available data from the region. An ideal “background” concentration is designated by EPA as being located in a rural setting upwind of the airport. Background concentrations were added to the model estimated concentrations for the airport sources to obtain total pollutant concentrations.

For the 24-hour period, the background is representative of the 98th percentile value of daily concentrations. Table 18 displays the monitoring sites near each case study airport and the value determined to represent background concentrations (shown in bold italics).

Importantly, the direct use of background concentrations may cause an underestimation of the total concentrations, as contributions from non-airport sources in the same geographic area as the airport (such as power plants) may not be fully accounted for. Similarly, if a monitoring site situated very close to the airport is used as a background site, the resultant concentrations may be an overestimation of the background values, as the monitoring station may already include a portion of the airport contribution.

Nevertheless, given that the focus of the ACRP 02-23 project is the airport sources and the impact that alternative fuels will have on the emissions and ambient $PM_{2.5}$, it is appropriate to select a representative value only so that an approximation of the total ambient $PM_{2.5}$ concentrations can be obtained.

Table 18 – Ambient Monitoring Data (μg/m^3)

Airport	Monitoring Station ID	Study Year	Concentration (μg/m^3)		Location from Airport	
			24-hour	Annual	Distance (mi)	Bearing
ATL	13-063-0091	2008	28.2	13.6	2.8	SE
	13-089-0002		***19.1***	***11.0***	8.7	ENE
	13-121-0048		24.8	11.8	10.0	N
	13-121-0032		24.0	13.4	12.8	N
	13-089-2001		21.8	12.3	20.1	NNE
LAS	32-003-0561	2008	22.5	9.07	6.2	NNE
	32-003-2002		18.8	8.88	7.8	NNE
	32-003-1019		***12.9***	***4.93***	23.3	SSW
MHT	33-011-1015	2007	29.9	10.3	11.8	S
	33-013-1006		26.6	9.67	13.8	N
	33-015-0014		***23.7***	***8.63***	36.2	ENE
PHL	34-015-5001	2004	***29.0***	***12.4***	3.7	SW
	42-101-0136		29.5	12.7	3.9	NNE
	42-101-0047		31.5	14.4	6.4	NE
	42-101-0004		34.3	13.9	12.1	NE
	42-101-0020		29.3	13.9	9.0	N
	42-101-0024		33.4	12.8	18.6	NE
	42-045-0002		30.5	15.0	7.4	WSW
	34-007-0003		35.0	13.3	8.4	ENE
SAN	06-073-1010	2008	24.8	13.2	3.2	SE
	06-073-0006		***21.5***	***11.8***	7.9	NNE
	06-073-1002		30.6	12.3	28.0	NNE
	06-073-0001		22.7	12.0	10.4	SE
	06-073-0003		26.0	13.4	15.0	ENE

Bold italics represent data used for background estimates
Source: U.S. EPA (2010b)

Development of Impacts for Alternative Fuels

For each scenario, the relative change in emissions between the base case and the alternative fuel scenario (scenario/base) were applied to the relevant source contribution's dispersion modeled results for each receptor point (i.e., individual locations) as indicated in Table 19 and Table 20.

Table 19 – Emission Changes and Application to Dispersion Source (Aircraft)

Fuel and Source Type	Scenario/Base Applied to Model Source
FT (natural gas) jet aircraft main engines high thrust non-volatile emissions	Takeoff Climb-out
FT (natural gas) jet aircraft main engines all thrust sulfur emissions	Approach Taxi-in Taxi-out Takeoff Climb-out
FT (natural gas) jet aircraft main engines high thrust volatile emissions	Takeoff Climb-out
FT (natural gas) jet aircraft main engines low thrust non-volatile emissions	Approach Taxi-in Taxi-out
FT (natural gas) jet aircraft main engines low thrust volatile emissions	Approach Taxi-in Taxi-out
FT (coal) jet aircraft main engines high thrust non-volatile emissions	Takeoff Climb-out
FT (coal) jet aircraft main engines all thrust sulfur emissions	Approach Taxi-in Taxi-out Takeoff Climb-out
FT (coal) jet aircraft main engines high thrust volatile emissions	Takeoff Climb-out
FT (coal) jet aircraft main engines low thrust non-volatile emissions	Approach Taxi-in Taxi-out
FT (coal) jet aircraft main engines low thrust volatile emissions	Approach Taxi-in Taxi-out
91/96UL AvGas for piston-engine aircraft approach	None
91/96UL AvGas for piston-engine aircraft idle	None
91/96UL AvGas for piston-engine aircraft takeoff	None
91/96UL AvGas for piston-engine aircraft climb	None
FT (natural gas) APU	Terminal/concourse
FT (coal) APU	Terminal/concourse
FT (natural gas) turboprop and turboshaft aircraft high thrust non-volatile emissions	None
FT (natural gas) turboprop and turboshaft aircraft low thrust non-volatile emissions	None
Electricity to replace some APU use	Terminal/concourse

Table 20 – Emission Changes and Application to Dispersion Source (Non-aircraft)

Fuel and Source Type	Scenario/Base Applied to Model Source
Electric GSE	Terminal/concourse
LPG GSE replacing diesel GSE	Terminal/concourse
CNG GSE replacing gasoline GSE	Terminal/concourse
CNG GSE replacing diesel GSE	Terminal/concourse
E10 in gasoline-fueled GSE	Terminal/concourse
B20 in diesel-fueled GSE	Terminal/concourse
B100 in diesel-fueled GSE	Terminal/concourse
Natural gas road vehicles to replace diesel	Internal roadways and parking (exhaust only)
Electric road vehicles	Internal roadways and parking (exhaust only)
E10 in gasoline-fueled road vehicles	Internal roadways and parking (exhaust only)
B20 in diesel-fueled road vehicles	Internal roadways and parking (exhaust only)
B100 in diesel-fueled road vehicles	Internal roadways and parking (exhaust only)

SENSITIVITIES OF ANALYSIS

As discussed in Chapter 2, there are four types of main aircraft engines: jet turbines, turbofans, turboprops (including turboshafts), and pistons. Within EDMS, aircraft $PM_{2.5}$ emissions are generated using FOA3a based on the HC emission factor, fuel flow, and smoke number (SN) data from the International Civil Aviation Organization's (ICAO) Engine Emissions Certification Databanks (2010). ICAO sets emission standards for jet turbines and turbofan engines greater than 26.7 kN of thrust, but not for turboprop, turboshaft or piston engines. Similarly, standards are not set for APUs.

Jet Turbines and Turbofans

There are some instances where EDMS does not calculate jet engine aircraft particulate matter emissions (i.e., where no ICAO related SN value exists or the value listed in ICAO is zero). Generally, EDMS uses the Calvert methodology (John, 2006), where a maximum SN exists and the relevant thrust SN is not available in ICAO. However, where the SN is listed as zero (as oppose to blank) in ICAO, EDMS assumes that the SN is zero, which results in no estimation of particulate matter emissions. The ICAO SN value is typically listed as zero because the SN is below the limit of detection for the equipment being used as oppose to actually being zero.

A number of manufacturers have started to report "0.01" where the limit of detection has been reached, rather than zero. Therefore, in instances where EDMS assumes a value of zero for SN for the ICAO zeros, alternative calculations have been undertaken for the ACRP 02-23 project, using a value of 0.01 for SN. The FOA3a was then applied in its detailed form, as presented by Wayson et al., (2009), to these new SN values to calculate non-volatile and volatile particulate matter. Since Wayson does not provide an estimate of particulate matter related to lubrication oils, this was taken from the PARTNER15 Project Report (Wayson et al., 2009; Ratliff et al., 2009).

Turboprop and Turboshaft Aircraft

As previously noted, EDMS does not typically include $PM_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no FAA accepted emission factors for these aircraft. As such, a number of turboprop and turboshaft aircraft particulate matter emissions data were used (as discussed in Chapter 2 and Appendix A) to compile a list of turboprop and turboshaft engine specific emission factors (particulate matter per fuel used in grams per kilogram, where particulate matter is assumed to be equivalent to $PM_{2.5}$). This list of engine emission factors was compared with turboprop and turboshaft engines utilized within the five case study airports and appropriate substitutions were made. Where there was no matching engine, an average turboprop (including turboshaft) engine $PM_{2.5}$ emission factor (g/kg) was used.

Of note, the FOA3a methodology is not applicable to turboprop or turboshaft engines. Consequently, no estimate of the non-volatile and volatile $PM_{2.5}$ emissions from turboprop or turboshaft engines can be made. Turboprop and turboshaft aircraft account for a small percentage of the total aircraft operations at larger airports such as ATL (only 3%), but up to 30% at airports such as MHT.

Piston-engine Aircraft

As discussed, EDMS does not estimate $PM_{2.5}$ from piston-engine aircraft. Therefore, soot emission factors (see Table 8, Appendix A) were used for all piston-engine aircraft as described in Appendix A. It was assumed that all AvGas was 100LL for the base case. Again, piston-engine aircraft account for a very small percentage of the total aircraft operations at larger airports (1%) and only 4% at MHT.

APPENDIX E: CASE STUDY AIRPORT RESULTS

Chapter 6 presents the case study airport emissions inventories and the range of emissions and other air pollution impacts for the alternative fuel scenarios compared to the base case. This Appendix presents detailed information relating to the base case and alternative fuel scenario emissions inventories and air quality impacts. The base case information describes relationships between the emissions from each source category for each case study airport. The detailed alternative fuels scenario information describes the change in emissions and air quality impact as a result of each scenario at each of the five case study airports.

BASE CASE

To provide a means of evaluating aircraft, ground support equipment (GSE) and auxiliary power unit (APU) emissions more consistently between the case study airports, the emissions of fine particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) were normalized as a function of the number of landing and takeoff (LTO) cycles as shown in Table 21 and Figure 18. For GSE and APU emissions, this is based on the total LTOs. However, for aircraft, this was based on the number of aircraft for which the Federal Aviation Administration’s (FAA) Emissions and Dispersion Modeling System (EDMS) calculated $PM_{2.5}$ emissions.

As shown, the general trends are similar for each case study airport with the highest per LTO emissions from aircraft, followed by GSE and APU. The GSE emissions per LTO are higher at Philadelphia International Airport (PHL) and lower at San Diego International Airport (SAN). 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. In addition, SAN is subject to more stringent Californian Air Resources Board (CARB) requirements on emissions control, which are designed to reduce fuel consumption and/or reduce pollutant emissions.

Table 21 – $PM_{2.5}$ Emissions Inventory (kg per LTO) for Aircraft-Related Sources

Source Category	ATL	LAS	PHL	SAN	MHT
Aircraft	0.087	0.073	0.092	0.097	0.097
Ground support equipment	0.020	0.014	0.063 (a)	0.005	0.021
Auxiliary power units	0.026	0.012	0.016	0.025	0.009

(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.

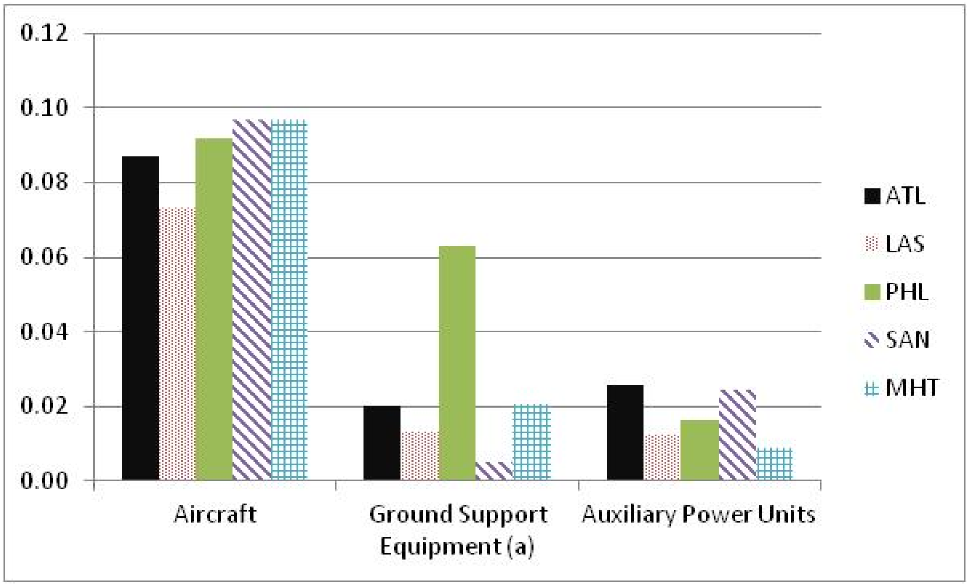


Figure 18 – Aircraft-Related Air Emissions Inventory (kg per LTO)

(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.

Aircraft $PM_{2.5}$ Emissions

Aircraft activity levels (i.e., aircraft arrival and departure operations) and aircraft and engine assignments were developed based on airport-specific information. As shown in Table 22 the aircraft emissions were further designated by operating mode for the assessment of non-volatile and volatile $PM_{2.5}$ emissions, since the level of aircraft-related emissions is a function of the time that an aircraft operates in each of the operational modes (i.e., an LTO cycle). An LTO cycle consists of the following operational modes:

- "Taxi/idle/delay" includes the time an aircraft taxis between the runway and a terminal, and all ground-based delay incurred through the aircraft route. The taxi and idle delay mode includes the landing roll, which is the movement of an aircraft from touchdown through deceleration to taxi speed to full stop.
- "Approach" begins when an aircraft descends below the atmospheric mixing height and ends when an aircraft touches down on a runway.
- "Takeoff" begins when full power is applied to an aircraft and ends when an aircraft reaches around 500 to 1,000 feet. At this altitude, pilots typically power back for a gradual ascent.
- "Climb-out" begins when an aircraft powers back from the takeoff mode and ascends above the atmospheric mixing height.

Although EDMS includes aircraft engine startup, it does not calculate $PM_{2.5}$ emissions during this mode.

Table 22 – Annual $PM_{2.5}$ Emissions Inventory by Aircraft Mode (kg)

Aircraft Mode	ATL	LAS	PHL	SAN	MHT
			Non-volatile Emissions		
Taxi-in	1,275	576	712	167	83
Taxi-out	836	682	679	282	73
Approach	1,274	376	1,046	512	90
Takeoff	5,453	4,728	3,319	1,738	364
Climb-out	2,868	1,675	1,364	718	170
Total non-volatile	**11,706**	**8,037**	**7,120**	**3,417**	**780**
			Volatile Emissions		
Taxi-in	3,994	1,064	1,423	238	138
Taxi-out	2,463	1,414	1,345	546	121
Approach	3,849	578	1,720	797	142
Takeoff	6,025	4,563	3,328	1,701	426
Climb-out	4,121	1,948	1,710	897	245
Total volatile	**20,452**	**9,567**	**9,526**	**4,179**	**1,073**
Grand total	**32,157**	**17,604**	**16,647**	**7,596**	**1,853**

As shown in Table 22, the approach mode represents between 5% and 17%, the taxi-in mode between 5% and 16%, and the taxi-out mode between 10% and 12% of the total aircraft $PM_{2.5}$ emissions. By comparison, the takeoff mode represents between 36% and 53%, and the climb-out mode represents between 18% and 22% of the total aircraft $PM_{2.5}$ emissions. For the entire LTO cycle, the non-volatile $PM_{2.5}$ emissions represent between 36% and 46% and the volatile $PM_{2.5}$ emissions represent between 54% and 64% of the total aircraft $PM_{2.5}$ emissions. To conclude, the largest proportion of aircraft emissions occur during takeoff and, in terms of volatile and non-volatile split, the volatile emissions generally dominate in all modes of the LTO cycle.

These findings reveal that a large proportion of the aircraft $PM_{2.5}$ emissions are related to airborne emissions, which have a smaller impact on $PM_{2.5}$ concentrations at ground level, even close to the airport than ground level emissions.

The EDMS aircraft $PM_{2.5}$ emissions were further segregated by aircraft type, as shown in Table 23. Note that Table 23 includes data from piston-engine aircraft for PHL only as these aircraft had user defined emissions included within the EDMS emissions inventory. Importantly, EDMS designations include business jet (e.g., Gulfstream V, Learjet 35), regional jet (e.g., CRJ-900, ERJ145, CL601), small jet (e.g., MD-83, 757-200, A320-200), medium jet (e.g., 767-300, 767-400, A330-300), and large jet (e.g., 777-300, A340-200).

These results show that small jets account for the largest amount of aircraft $PM_{2.5}$ emissions (between 48% and 86%, depending on the airport). This is followed by medium sized and regional jets. Business and large jets make up the remaining percentage and their contribution is mostly dependent of the type of service at the airport (e.g., commercial, cargo).

Table 23 – Annual $PM_{2.5}$ Emissions Inventory by Aircraft Type (kg)

Aircraft Type	ATL	LAS	PHL	SAN	MHT
Business jet	1,298	771	408	366	178
Regional jet	8,756	342	2,037	812	357
Small jet	15,382	15,225	10,391	5,606	1,101
Medium jet	4,108	632	2,171	728	161
Large jet	2,612	634	1,371	85	56
User defined piston	0	0	269	0	0
Total	**32,157**	**17,604**	**16,647**	**7,596**	**1,853**

Note: EDMS 5.1.2 designations include business jet (Gulfstream V, Learjet 35), regional jet (CRJ-900, ERJ145, CL601), small jet (MD-83, 757-200, A320-200), medium jet (767-300, 767-400, A330-300), and large jet (777-300, A340-200)

Again, to provide a means of comparing airports, the aircraft emissions normalized per jet LTO by aircraft type are displayed in Table 24 and Figure 19. EDMS does not typically include $PM_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no FAA accepted emission factors for these aircraft (see the Sensitivities of Analysis section at the end of this Appendix for an estimate of these aircraft emissions). Therefore, the emissions have been divided by the number of LTOs for aircraft that have $PM_{2.5}$ emissions data in EDMS. The number of LTOs for some aircraft types at some of the case study airports is very low (such as medium jets at MHT). Thus, the emissions per LTO may be of limited value in these cases. In general, small, business and regional jets have lower $PM_{2.5}$ emission per LTO compared with larger jets and $PM_{2.5}$ emissions per LTO generally increase from small, to medium, to large jets.

Table 24 – $PM_{2.5}$ Emissions Inventory by Aircraft Type (kg per LTO)

Aircraft Type	ATL	LAS	PHL	SAN	MHT
Business jet	0.109†	0.062†	0.074†	0.081†	0.082
Regional jet	0.047	0.073†	0.036	0.083†	0.167
Small jet	0.104	0.071	0.100	0.096	0.071
Medium jet	0.180†	0.092†	0.187†	0.218†	0.551†
Large jet	0.437†	0.320†	0.715†	0.038†	0.120†
Weighted Average	**0.087**	**0.073**	**0.092**	**0.097**	**0.097**

Note: EDMS5.1.2 designations include business jet (Gulfstream V, Learjet 35), regional jet (CRJ-900, ERJ145, CL601), small jet (MD-83, 757-200, A320-200), medium jet (767-300, 767-400, A330-300), and large jet (777-300, A340-200).

† Based on less than 10% of the total aircraft LTOs.

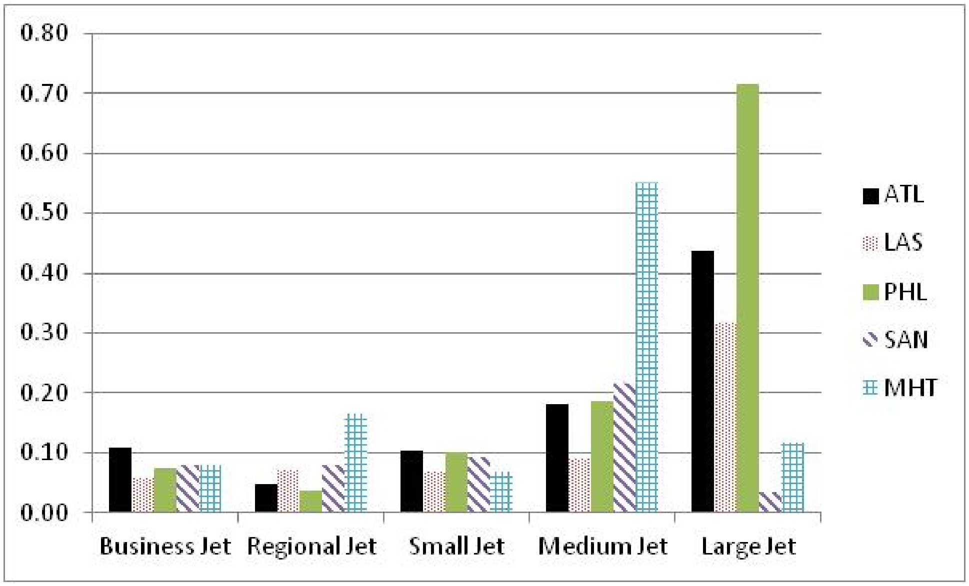


Figure 19 – $PM_{2.5}$ Emissions Inventory by Aircraft Type (kg per LTO)

Ground Support Equipment

The type of GSE analyzed included aircraft tugs, baggage tugs, belt loaders, fuel trucks, water trucks, lavatory trucks and cargo loaders. Air emissions resulting from the operation of GSE vary depending on the type of equipment, fuel type (e.g., gasoline, diesel, propane, electric), and the duration of equipment operation (engine run time). The type of GSE used depends on the aircraft type and the designated category of an aircraft operation (e.g., passenger, cargo).

The results in Table 25 show that for GSE emissions, the majority (i.e., greater than 70%) of $PM_{2.5}$ emissions are due to the operation of diesel-fueled equipment. Each of the five case study airports has its own airport-specific GSE fleet and fuel type, the latter partly a function of the geographic location, the airline's preferences and the air quality regulations in the region. Secondly, the unavailability of airport-specific data required the use of EDMS default data, which can modify the results of an emissions inventory.

Table 25 – Annual $PM_{2.5}$ Emissions Inventory by GSE Fuel Type (kg)

Fuel Type	ATL	LAS	PHL	SAN	MHT
Gasoline	3,230	713	555	19	102
Diesel	6,600	3,300	14,385 (a)	559	843
CNG	-	-	-	3	-
LPG	-	101	-	-	-
Total	**9,829**	**4,114**	**14,940**	**582**	**945**

Note: A dash (-) indicates that no data were available for these sources

(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.

Table 26 contains the GSE emissions data by GSE type and fuel type. Electric equipment is not listed as it does not emit direct $PM_{2.5}$ emissions. The majority of the $PM_{2.5}$ emissions is attributable to aircraft tractors, baggage tractors, belt loaders, and support trucks (e.g., catering, cabin service and lavatory). Again, each of the five case study airports has its own specific GSE fleet mix and some airports have more or less gasoline/diesel equipment, some require deicers or air-conditioners and some have greater use of ground power units. For example, 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.

To some degree, the GSE emissions are also a function of the data (i.e., using default data or the collection of actual GSE vehicle types, fuel types and operating times) used for this analysis. For example, some airports have a greater amount of airport-specific data available, and this may yield estimates closer to actual values. In other words, the greater use of default data may result in underestimation or overestimation of the actual emissions. Nevertheless, the general conclusions on fuel and equipment trends and the resultant $PM_{2.5}$ emissions still apply.

Table 26 – Annual $PM_{2.5}$ Emissions Inventory by GSE and Fuel Type (kg)

GSE Type	Fuel Type	ATL	LAS	PHL (a)	SAN	MHT
Aircraft tractor	Diesel	2,535	556	1,002	219	110
	Gasoline	-	2	5	-	-
Air-conditioner	Diesel	-	8	-	-	-
Air start	Diesel	276	6	2,260	29	78
	Gasoline	-	-	-	<0.5	-
Baggage tractor	Diesel	-	421	5,174	55	93
	Gasoline	1,479	150	154	6	37
	LPG	-	1	-	-	-
Belt loader	Diesel	-	984	2,892	37	169
	Gasoline	1,731	427	43	3	16
	LPG	-	1	-	-	-
Cabin service truck	Diesel	1,098	451	558	-	67
	Gasoline	-	-	9	-	-
Cargo loader	Diesel	982	206	489	32	57
	Gasoline	-	-	4	-	-
Cargo tractor	Diesel	-	41	-	-	-
	Gasoline	-	5	-	-	-
Cart	Gasoline	-	1	-	<0.5	-
Catering truck	Diesel	1,370	176	422	-	36
	Gasoline	-	27	6	5	-
	LPG	-	98	-	-	-
Deicer	Gasoline	-	3	-	-	22
Fork lift	Diesel	8	-	-	3	-
	Gasoline	-	1	-	-	-

GSE Type	Fuel Type	ATL	LAS	PHL (a)	SAN	MHT
	CNG	-	-	-	3	-
	LPG	-	2	-	-	-
Fuel truck	Diesel	117	90	381	33	86
	Gasoline	-	-	25	<0.5	-
Generator	Diesel	-	58	-	-	-
	Gasoline	-	-	-	<0.5	-
Ground power unit	Diesel	26	131	953	147	89
	Gasoline	20	26	5	2	26
Hydrant truck	Diesel	-	-	152	-	-
Lavatory truck	Diesel	144	14	57	1	20
	Gasoline	-	23	49	<0.5	1
Lift	Diesel	-	35	-	<0.5	-
	Gasoline	-	-	-	<0.5	-
Other	Diesel	-	25	-	1	-
Passenger stand	Diesel	-	-	-	1	-
	Gasoline	-	-	-	<0.5	-
Service truck	Diesel	43	97	46	-	37
	Gasoline	-	48	127	1	-
Sweeper	Diesel	-	3	-	-	-
Water truck	Gasoline	-	<0.5	128	-	-
Total		**9,829**	**4,114**	**14,940**	**582**	**945**

Note: A dash (-) indicates that no data were available for these sources, either because the airport does not have the specified equipment/fuel type or the airport did not provide data for the specified equipment/fuel type

(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.

Auxiliary Power Units

APUs are onboard aircraft engines that provide power, heat and air-conditioning to aircraft while taxiing or at the terminal gate. APUs can also be used to start the engines before departing from the gate area. EDMS assigns default APUs based on aircraft assignments and also includes pollutant emission factors corresponding to the horsepower for each unit. Table 27 contains the $PM_{2.5}$ emissions inventory results for APUs. The APU emissions tend to be higher for the larger airports and lower for the smaller airports.

Table 27 – Annual $PM_{2.5}$ Emissions Inventory (kg) for APU

Source Category	ATL	LAS	PHL	SAN	MHT
Auxiliary power units	12,617	3,800	3,802	2,730	425

Road Vehicles

For most airports, road vehicle emissions occur at parking lots and at on-airport and off-airport roadways, as shown in Table 28. The level of emissions that result from the operation of airport-related road vehicles depends on several factors, including:

- Volume of road vehicles
- Vehicle fleet mix
- Road vehicle emission factors
- Travel distance
- Vehicle speed
- Vehicle model year

Road vehicles include privately owned vehicles (e.g. cars, vans, trucks, cabs, rental cars), mass transit vehicles (e.g., buses and vans), airport-owned vehicles (e.g., shuttles, buses), and delivery vehicles (e.g., trucks and vans).

Emissions from road vehicles in parking facilities are a result of:

- Total time vehicles spend idling in a parking facility
- Distance vehicles travel in the facility
- Speed of the vehicles
- Type of vehicle

Table 28 – Annual $PM_{2.5}$ Emissions Inventory for Road Vehicles (kg)

Roadways and Parking Lots	ATL	LAS	PHL	SAN	MHT
On-Airport Emissions					
Exhaust (non-volatile)	995	128	846	277	52
Exhaust (volatile)	474	18	416	70	20
Brake And Tire	634	243	283	60	25
Total Onsite	**2,103**	**389**	**1,545**	**407**	**96**
Off-Airport Emissions					
Exhaust (non-volatile)	11,802	1,349	6,749	1,109	22
Exhaust (volatile)	4,699	401	3,216	455	8
Brake and tire	5,265	1,325	2,256	462	10
Total Offsite	**21,766**	**3,073**	**12,221**	**2,026**	**41**

Roadway and parking lot road vehicle emissions were also computed on a per enplanement basis (i.e., passenger) for each airport to provide a better means of comparison (see Table 29). Airport enplanement values are readily available, and those values provide a general estimate of the roadway emissions. As the geographic roadway coverage varies from airport to airport, the emission rates per vehicle mile were also calculated, resulting in a range from 0.02 to 0.07 grams per vehicle mile. However, an airport's vehicle miles traveled are not always readily available (where spatial data are not available) but, as it provides a more precise comparison of the roadway emissions between airports, it has been included.

Table 29 – Road vehicle $PM_{2.5}$ Emissions Inventory – Emission Factors

Source Category	ATL	LAS	PHL	SAN	MHT
Emissions (kg) per 1,000 enplanement					
On-airport roadways	0.03	0.01	0.06	0.02	0.05
Off-airport roadways	0.28	0.07	0.5	0.11	0.02
Emissions (grams) per vehicle mile					
On-airport roadways	0.04	0.02	0.05	0.07	0.03
Off-airport roadways	0.03	0.02	0.07	0.03	0.03

Stationary Sources and Fire Training

Stationary sources of $PM_{2.5}$ emissions at airports include boilers, generators, snow melters, cooling towers, painting operations, aircraft engine test facilities, and fire training facilities. These sources, their size, fuel type, and use can vary greatly from airport to airport as a result of the airport's size and climate. Of the five case study airports, LAS has a number of on-airport boilers and cooling towers and PHL includes a fire training facility (see Table 30).

Table 30 – Annual $PM_{2.5}$ Emissions Inventory (kg) for Stationary Sources and Fire Training

Source Category	ATL	LAS	PHL	SAN	MHT
Stationary Sources					
Boilers	218	1,153	392	90	47
Generators	230	642	-	498	12
Cooling Towers	-	3,664	-	-	-
Miscellaneous	-	-	-	-	6
Total Stationary Sources	**448**	**5,459**	**392**	**588**	**66**
Fire Training					
Fire Training	-	-	2,819	-	-

Note: A dash (-) indicates that no data were available for these sources, either because the airport does not have the specified emission sources or the airport did not provide data for the specified emission sources

Ambient Monitoring Data

Background $PM_{2.5}$ concentrations were determined for each case study airport. Table 31 contains those 24-hour concentrations (noted as the maximum of the 98th percentile) and the annual average $PM_{2.5}$ concentrations. These data are used in support of the dispersion modeling discussed in the next section.

Table 31 – Background Concentration (µg/m^3)

Source	ATL	LAS	PHL	SAN	MHT
24-hour	19.1	12.9	29.0	21.5	23.7
Annual	11.0	4.9	12.4	11.8	8.6

Source: U.S. EPA (2010b)

Dispersion Modeling Analysis

The AERMOD dispersion model incorporated in EDMS was used to estimate ambient (i.e., outdoor) concentrations of $PM_{2.5}$ on, and in the vicinities 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 modeled results (i.e., by terminal area/concourse, aircraft mode, and internal and external roadways) and AERMOD (Version 09292) run outside of EDMS. AERMOD is the EPA preferred dispersion model for general industrial sources.

The dispersion modeling results are represented by the concentrations for the receptor at which the maximum concentration occurs, the radius of influence (ROI, defined as the distance that extends from the source (in this case, the airport reference point) to the farthest receptor distance at which the source has a concentration greater than a specific threshold for a given pollutant) and the influence area (i.e., the area within a threshold concentration level). Depending on the location of a receptor, the concentration (maximum or otherwise) may be dominated by aircraft, GSE and APU, road vehicle or stationary sources.

Average Annual $PM_{2.5}$ Concentrations

The dispersion modeling analysis computed annual average $PM_{2.5}$ concentrations in micrograms per cubic meter ($\mu g/m^3$) for each receptor contained in the discrete and polar receptor grids set up for the case study airports. Table 32 displays, the maximum airport-related annual $PM_{2.5}$ concentrations and the annual $PM_{2.5}$ concentrations by source category, for the same overall maximum receptor, and for each airport. The background $PM_{2.5}$ and the total $PM_{2.5}$ concentrations are also shown in Table 32. The contributions of source categories to the maximum receptor concentrations are highly variable and depend on the exact location of the receptor and the receptors proximity to the various source categories.

Table 32 – $PM_{2.5}$ Dispersion Modeling Results – Maximum Annual ($\mu g/m^3$)

Source	ATL	LAS	PHL	SAN	MHT
Aircraft	0.27	0.20	0.21	0.07	0.03
Gates	1.03	0.63	0.75	1.38	2.33
Roadways	0.12	0.46	0.28	0.75	0.01
Parking facilities	0.27	0.03	0.01	0.20	0.02
Stationary sources and fire training	0.01	1.46	0.01	0.07	0.00
Subtotal	**1.70**	**2.77**	**1.26**	**2.47**	**2.40**
Background	11.00	4.93	12.40	11.80	8.63
Total	**12.70**	**7.70**	**13.67**	**14.27**	**11.03**
NAAQS	**15.0**	**15.0**	**15.0**	**15.0**	**15.0**

As shown, the gate activities (i.e., GSE and APU) generally contribute the greatest percentage to the overall airport-related $PM_{2.5}$ concentrations. Exceptions include LAS where stationary sources are a majority. These results are highly dependent on source emission strengths, source locations relative to receptors and meteorological data. Given MHT's small size, the location of the public access receptors may be closer to the apron area and, thus, have a large contribution of

GSE and APU impact at the maximum receptor. Conversely, ATL may have a greater distance between the aprons and the public access receptors and, thus, have a smaller percentage contribution from GSE and APU.

Gate-related $PM_{2.5}$ emissions extend over a wide area. However, $PM_{2.5}$ emissions from aircraft, roadways and stationary sources are generally confined to the runways and taxiways, along the roadways and in other isolated areas of the airport. The concentrations associated with these sources disperse more rapidly with distance.

Table 33 and Figure 20 present the maximum annual concentration (airport contribution only) as a function of distance from the airport reference point (as provided within EDMS).

Table 33 – $PM_{2.5}$ Dispersion Modeling Results – Maximum Annual (μg/m^3) by Distance (meters)

Distance (km)	ATL	LAS	PHL	SAN	MHT
0.5	-	-	-	1.28	1.28
1.0	-	2.77	-	2.47	2.40
1.5	-	2.14	1.02	2.34	1.59
2.0	1.70	1.25	1.26	1.41	0.27
2.5	1.23	1.17	0.82	0.71	0.17
3.0	0.79	1.25	0.75	0.46	0.11
4.0	0.39	1.01	0.30	0.30	0.07
5.0	0.30	0.26	0.21	0.21	0.04
6.0	0.20	0.20	0.14	0.16	0.03
7.0	0.17	0.16	0.11	0.14	0.02
8.0	0.15	0.13	0.08	0.11	0.02
9.0	0.11	0.10	0.07	0.09	0.01
10.0	0.10	0.09	0.06	0.07	0.01

Note: A dash (-) indicates within airport property. Values do not include background concentrations.

As shown in Figure 0, the annual average concentration at a distance of 5 km is much lower than the overall maximum concentration.

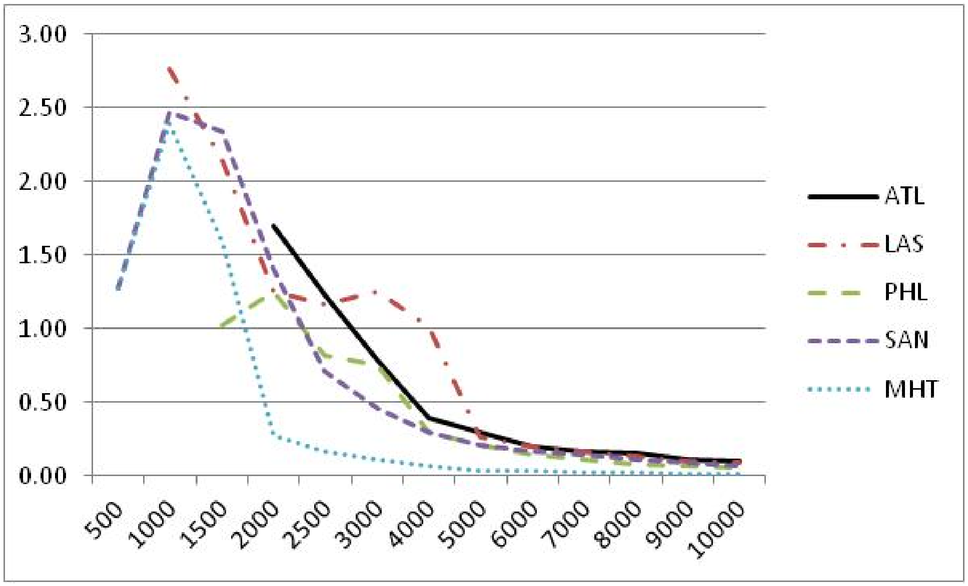


Figure 20 – Air Dispersion Modeling Results – Annual Concentration (µg/m^3) by Distance (meters)

24-hour $PM_{2.5}$ Concentrations

Table 34 presents the maximum 98th percentile 24-hour $PM_{2.5}$ (represented as the seventh highest value at any given receptor) concentrations for each case study airport, the background concentration and the total concentration. These results are further broken down by each airport source category. The contributions of source categories to the maximum receptor concentrations are highly variable and depend on the exact location of the receptor and the receptors' proximity to the various source categories.

As shown, the terminal gate sources (i.e., GSE and APU) again generally contribute the greatest percentage to the overall concentration. The exception is LAS, where stationary sources are a majority. As with the annual $PM_{2.5}$ concentration results, the gate source emissions are spread out over a wide area, while the airport runway and taxiway, roadway and stationary sources are comparatively more confined in their spatial distribution, especially at ground level.

Table 34 – $PM_{2.5}$ Dispersion Modeling Results – Maximum 24-hour (µg/m^3)

Source	ATL	LAS	PHL	SAN	MHT
Aircraft	0.96	0.34	0.46	0.33	0.01
Gates	4.54	1.50	4.37	3.50	4.10
Roadways	0.58	<0.01	0.24	0.07	<0.01
Parking facilities	0.25	0.08	0.04	0.02	<0.01
Stationary sources	0.01	2.71	0.03	0.07	0.03
Subtotal	**6.34**	**4.63**	**5.14**	**3.99**	**4.15**
Background	19.1	12.9	29.0	21.5	23.7
Total	**25.4**	**17.5**	**34.1**	**25.5**	**27.9**
NAAQS	**35.0**	**35.0**	**35.0**	**35.0**	**35.0**

Table 35 and Figure 21 present the maximum 24-hour 98th percentile concentration (airport contribution only) as a function of distance from the airport center point.

Table 35 – $PM_{2.5}$ Dispersion Modeling Results – Maximum 24-hour (µg/m^3) by Distance (meters)

Distance (km)	ATL	LAS	PHL	SAN	MHT
0.5	-	-	-	2.24	4.15
1.0	-	4.63	-	3.99	3.90
1.5	-	3.85	4.53	3.62	3.62
2.0	6.34	2.54	5.14	2.32	0.95
2.5	5.52	2.95	4.46	1.68	0.64
3.0	3.64	2.67	3.23	1.11	0.49
4.0	2.11	2.01	1.95	0.82	0.31
5.0	1.53	0.69	1.30	0.57	0.23
6.0	1.04	0.51	1.09	0.56	0.18
7.0	0.92	0.43	0.99	0.46	0.15
8.0	0.88	0.35	0.70	0.40	0.12
9.0	0.73	0.29	0.56	0.32	0.09
10.0	0.65	0.25	0.52	0.30	0.08

Note: A dash (-) indicates within airport property. Values do not include background concentrations

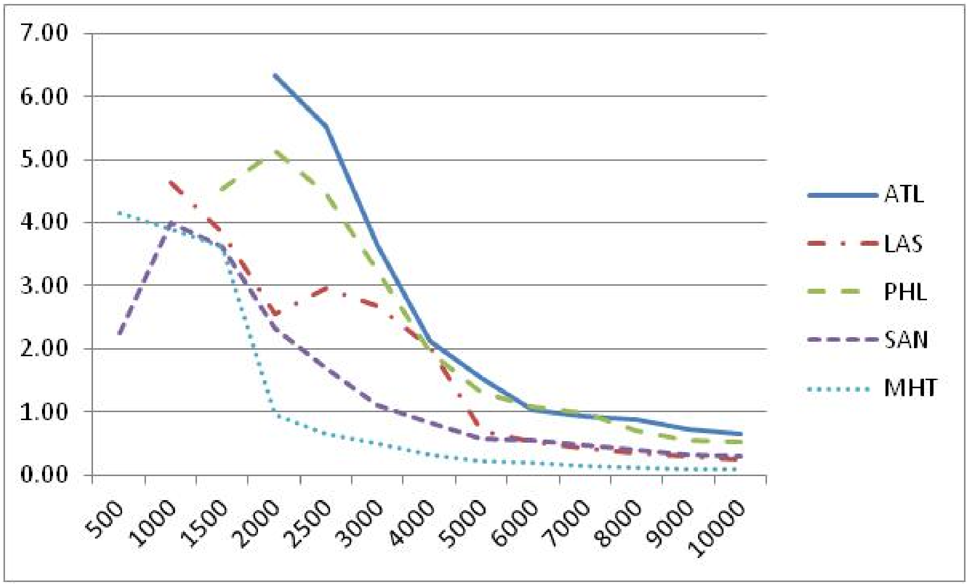


Figure 21 – Air Dispersion Modeling Results – Maximum 24-hour Concentration (µg/m^3) by Distance (meters)

Radius of Influence (ROI)

For stationary source permitting, the EPA's Prevention of Significant Deterioration (PSD) Program defines a pollutant concentration threshold to estimate the ROI. For $PM_{2.5}$, these concentration thresholds are 1.2 µg/m^3 for a 24-hour 98th percentile concentration and 0.3 µg/m^3 for annual concentrations (U.S. EPA, 2010d). The ROI is the furthest distance from a source (in this case, the airport reference point within EDMS) where all receptor concentrations are below the threshold. Thus, concentrations at all receptors beyond this distance would be below the threshold. However, not all receptors within this distance would be above the thresholds as source location and meteorological conditions affect the direction and extent of the concentrations.

These ROI concentration thresholds are a small fraction (about 5%) of the NAAQS and could be considered analogous to an audible noise level. The ROI concentration thresholds are not to be compared or related to any significance threshold for the National Environmental Policy Act (NEPA) and project-related effects. Table 36 provides a summary of the ROI for each of the five case study airports.

Table 36 – $PM_{2.5}$ Dispersion Modeling Results – Radius of Influence (meters)

Averaging Period	ATL	LAS	PHL	SAN	MHT
24-hour	5,674	4,614	5,487	2,920	1,953
Annual	4,968	4,952	4,012	4,018	1,988

Influence Area

Based on the concentrations and the ROI concentration thresholds, an influence area (in acres) can be determined. The influence area is designated as the area represented by the receptors above the ROI concentration thresholds. Table 37 provides a summary of the influence area for each of the five case study airports.

This influence area is a subset of the ROI. Thus, the concentration isopleth fits within the ROI with the furthest extent of the isopleth equal to the ROI, but the area represents only those receptors greater than the ROI concentration threshold. Of note, a portion of the influence area would be on-airport and off-airport and, in part, is a function of the size of the particular airport.

Table 37 – $PM_{2.5}$ Dispersion Modeling Results – Influence Area (acres)

Averaging Period	ATL	LAS	PHL	SAN	MHT
24-hour	14,322	3,647	11,515	1,390	364
Annual	9,129	5,079	6,445	2,511	454

SENSITIVITIES OF ANALYSIS

As noted in Chapter 4, EDMS does not typically include $PM_{2.5}$ emission results for piston-engine, turboprop, and turboshaft aircraft as there are no FAA accepted emission factors for these aircraft. The following section presents a sensitivity analysis of the estimated $PM_{2.5}$ from those aircraft for which EDMS does not include emission calculations. This comparison demonstrates the sensitivity of the local $PM_{2.5}$ impacts from an aircraft fleet mix at airports with high numbers of turboprop, turboshaft and piston-engine aircraft, and other aircraft not estimated by EDMS (see Table 38). The second portion of Table 38 shows the number of aircraft LTO cycles for which EDMS does and does not provide $PM_{2.5}$ emission calculations. This potential issue has implications for the calculated ambient (dispersion modeled) concentrations.

Table 38 – Annual $PM_{2.5}$ Emissions Inventory (kg) for Aircraft

Condition	ATL	LAS	PHL	SAN	MHT
Aircraft Emissions					
$PM_{2.5}$ emissions within EDMS	32,157	17,604	16,647	7,596	1,853
$PM_{2.5}$ emissions not within EDMS (aircraft specific)	8,920	2,597	4,906	2,272	2,432
$PM_{2.5}$ emissions not within EDMS (scaled)	183	421	1,033	151	539
Total	41,260	20,622	22,586	10,019	4,823
Aircraft LTOs					
$PM_{2.5}$ emissions within EDMS	340,180	191,690	182,560	59,892	19,117
$PM_{2.5}$ emissions not within EDMS	148,920	112,696	54,678	50,055	26,719
Total	489,100	304,386	237,238	109,947	45,836

Table 39 depicts the percentage of increased emissions relative to the EDMS-generated emissions. Results from the sensitivity analysis indicate that, at the case study airports, aircraft emissions could more than 17% higher than reported by EDMS. At smaller airports, where the proportion of piston-engine, turboprop and turboshaft aircraft is much higher, the increase in aircraft emissions could be much more substantial.

Table 39 – Annual $PM_{2.5}$ Emissions Inventory (percent emissions increase) for Aircraft

Condition	ATL	LAS	PHL	SAN	MHT
$PM_{2.5}$ emissions not within EDMS (aircraft specific)	28	15	29	30	131
$PM_{2.5}$ emissions not within EDMS (scaled)	1	2	6	2	29
Total	**29**	**17**	**35**	**32**	**160**

Of note, the dispersion modeling analysis shows that aircraft activities do not provide the largest contribution to the maximum concentrations. This remains the case even if the results are scaled in line with the above uncertainties. This is due to the distance the emissions have to travel to the receptor after the aircraft leaves the ground. Secondly, the largest aircraft emissions contribution is during the takeoff mode and other above-ground operating conditions. Thus, although important to the magnitude of the emissions inventory, the discounting of turboprop, turboshaft, and piston-engine aircraft $PM_{2.5}$ emissions inherent in the EDMS may not change the dispersion modeling results or conclusions materially.

As described in Chapter 5, the aircraft emissions inventory was conducted using an atmospheric mixing height of 3,000 feet (the default value within EDMS) for all airports. However, actual mixing heights vary as a function of climate, geography, altitude, ground cover, and the proximity to urban areas and bodies of water. Table 40 provides a comparison between the aircraft emissions with the airport-specific mixing height and the 3,000 foot default value. The mixing heights for LAS are generally higher due to the arid, high-altitude climate. As a result, the actual emissions are much greater for LAS than those assuming a mixing height of 3,000 feet.

Table 40 – Annual $PM_{2.5}$ Emissions Inventory (kg) for Aircraft by Mixing Height

Condition	ATL	LAS	PHL	SAN	MHT
Actual Mixing Height	30,787	24,074	16,250	6,783	1,768
Mixing Height of 3,000 feet	32,157	17,604	16,647	7,596	1,853

ALTERNATIVE FUEL SCENARIOS

The following tables present the detailed data and results of the base case and alternative fuel scenarios for each of the five case study airports. These results provide the data from which the summaries were presented in Chapter 6.

Table 41 presents the airport wide annual emissions inventory for the base case and alternative fuel scenarios, while Table 42 presents the magnitude change and percentage change in airport wide annual emissions for the alternative fuel scenarios compared with the base case. A similar set of tables are presented for the following:

- Table 43 and Table 44 present the maximum 24-hour 98th percentile concentration results.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.
- Table 45 and Table 46 present the annual maximum concentration results.
- Table 47 and Table 48 present the 24-hour 98th percentile ROI.
- Table 49 and Table 50 present the annual ROI.
- Table 51 and Table 52 present the 24-hour 98th percentile influence area.
- Table 53 and Table 54 present the annual influence area.

Of note, the results represent analysis of the five case study airports; other airports may fall into a similar range of results or outside the range found for the case study airports, depending on their specific operating conditions.

Table 55 presents the emissions inventory for the alternative fuel scenarios related to turboprop (including turboshaft) and piston-engine aircraft.

Table 41 – Annual $PM_{2.5}$ Emissions Inventory for Base Case and Alternative Fuel Scenarios (kg)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	78,920	34,440	52,366	13,928	3,426
100% FT (natural gas) aircraft and APU	56,748	23,504	42,235	8,773	2,288
100% FT (coal) aircraft and APU	58,655	24,849	43,339	9,331	2,414
100% Gate power and pre-conditioned air (PCA) to replace APU use	72,830	33,267	50,822	12,346	3,332
100% Electric GSE, where model available	69,535	30,740	40,416	13,421	2,704
100% LPG GSE replacing diesel GSE, where model available	74,528	32,658	41,615	13,551	2,801
100% CNG GSE replacing gasoline GSE, where model available	78,594	34,386	52,212	14,249	3,373
100% CNG GSE replacing diesel GSE, where model available	74,528	32,658	41,615	13,551	2,801
E10 in 100% gasoline-fueled GSE	77,628	34,421	52,144	13,927	3,385
B20 in 100% diesel-fueled GSE	78,129	34,415	50,641	13,895	3,325
B100 in 100% diesel-fueled GSE	75,806	34,342	45,578	13,795	3,028
B100 in 50% diesel-fueled GSE	77,363	34,391	48,972	13,862	3,227
Natural gas road vehicles to replace diesel (9% of market)	78,920	34,440	52,365	13,928	3,426
Natural gas road vehicles to replace diesel (32% of market	78,918	34,440	52,365	13,928	3,426
Natural gas road vehicles to replace diesel (100% of market)	78,914	34,440	52,363	13,928	3,326
Electric road vehicles (5% of market)	78,847	34,433	52,302	13,911	3,423
Electric road vehicles (10% of market)	78,773	34,425	52,239	13,894	3,419
Electric road vehicles (100% of market)	77,452	34,294	51,104	13,581	3,355
E10 in 100% gasoline-fueled road vehicles	78,793	34,383	52,251	13,793	3,419
B20 in diesel-fueled road vehicles (12.8% of market)	78,911	34,440	52,351	13,928	3,425
B20 in diesel-fueled road vehicles (100% of market)	78,851	34,439	52,249	13,927	3,420
B100 in diesel-fueled road vehicles (2.6% of market)	78,913	34,440	52,354	13,928	3,425
B100 in diesel-fueled road vehicles (6% of market)	78,904	34,440	52,338	13,928	3,425
B100 in diesel-fueled road vehicles (100% of market)	78,647	34,438	51,905	13,924	3,401

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.

Table 42 – Alternative Fuel Scenario versus Base Case Annual $PM_{2.5}$ Emissions Inventory

Condition	Change in Annual Emissions (kg) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-22,172	-10,936	-10,131	-5,156	-1,138	-28	-32	-19	-37	-33
100% FT (coal) aircraft and APU	-20,265	-9,591	-9,027	-4,597	-1,012	-26	-28	-17	-33	-30
100% Gate power and PCA to replace APU use	-6,090	-1,173	-1,544	-1,582	-94	-8	-3	-3	-11	-3
100% Electric GSE, where model available	-9,385	-3,700	-11,950	-508	-722	-12	-11	-23	-4	-21
100% LPG GSE replacing diesel GSE, where model available	-4,392	-1,781	-10,751	-378	-626	-6	-5	-21	-3	-18
100% CNG GSE replacing gasoline GSE, where model available	-326	-54	-154	321	-53	0	0	0	2	-2
100% CNG GSE replacing diesel GSE, where model available	-4,392	-1,781	-10,751	-378	-626	-6	-5	-21	-3	-18
E10 in 100% gasoline-fueled GSE	-1,292	-19	-222	-2	-41	-2	0	0	0	-1
B20 in 100% diesel-fueled GSE	-791	-25	-1,725	-34	-101	-1	0	-3	0	-3
B100 in 100% diesel-fueled GSE	-3,114	-98	-6,788	-133	-398	-4	0	-13	-1	-12
B100 in 50% diesel-fueled GSE	-1,557	-49	-3,394	-66	-199	-2	0	-6	0	-6
Natural gas road vehicles to replace diesel (9% of market)	-1	0	-1	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	-2	0	-1	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	-6	0	-3	0	0	0	0	0	0	0
Electric road vehicles (5% of market)	-73	-7	-64	-17	-4	0	0	0	0	0
Electric road vehicles (10% of market)	-147	-15	-127	-35	-7	0	0	0	0	0
Electric road vehicles (100% of market)	-1,469	-146	-1,262	-347	-72	-2	0	-2	-2	-2
E10 in 100% gasoline-fueled road vehicles	-127	-57	-115	-135	-7	0	0	0	-1	0
B20 in diesel-fueled road vehicles (12.8% of market)	-9	0	-15	0	-1	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	-70	0	-117	-1	-6	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	-7	0	-12	0	-1	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	-16	0	-28	0	-2	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-274	-2	-461	-4	-25	0	0	-1	0	-1

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.

Table 43 – Maximum 24-hour $PM_{2.5}$ Dispersion Modeling Results for Base Case and Alternative Fuel Scenarios (µg/m^3)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	6.34	4.63	5.14	3.99	4.15
100% FT (natural gas) aircraft and APU	4.92	4.14	4.52	2.52	3.56
100% FT (coal) aircraft and APU	4.96	4.16	4.55	2.55	3.56
100% Gate power and pre-conditioned air (PCA) to replace APU use	5.76	4.55	4.77	2.41	3.95
100% Electric GSE, where model available	3.96	3.87	2.36	3.50	2.01
100% LPG GSE replacing diesel GSE, where model available	5.25	4.40	2.66	3.63	2.26
100% CNG GSE replacing gasoline GSE, where model available	6.27	4.61	5.10	4.34	4.09
100% CNG GSE replacing diesel GSE, where model available	5.25	4.40	2.66	3.63	2.26
E10 in 100% gasoline-fueled GSE	6.03	4.63	5.08	3.99	4.07
B20 in 100% diesel-fueled GSE	6.14	4.63	4.74	3.96	3.84
B100 in 100% diesel-fueled GSE	5.56	4.63	3.56	3.86	2.94
B100 in 50% diesel-fueled GSE	5.95	4.63	4.35	3.93	3.54
Natural gas road vehicles to replace diesel (9% of market)	6.34	4.63	5.14	3.99	4.15
Natural gas road vehicles to replace diesel (32% of market	6.34	4.63	5.14	3.99	4.15
Natural gas road vehicles to replace diesel (100% of market)	6.34	4.63	5.14	3.99	4.15
Electric road vehicles (5% of market)	6.33	4.63	5.13	3.99	4.15
Electric road vehicles (10% of market)	6.32	4.63	5.13	3.99	4.15
Electric road vehicles (100% of market)	6.16	4.60	5.07	3.97	4.15
E10 in 100% gasoline-fueled road vehicles	6.28	4.62	5.13	3.98	4.15
B20 in diesel-fueled road vehicles (12.8% of market)	6.34	4.63	5.14	3.99	4.15
B20 in diesel-fueled road vehicles (100% of market)	6.34	4.63	5.13	3.99	4.15
B100 in diesel-fueled road vehicles (2.6% of market)	6.34	4.63	5.14	3.99	4.15
B100 in diesel-fueled road vehicles (6% of market)	6.34	4.63	5.14	3.99	4.15
B100 in diesel-fueled road vehicles (100% of market)	6.33	4.63	5.11	3.99	4.15

Note 1: Concentration represents airport contribution (does not include background) at the maximum receptor.
Note 2: 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.

Table 44 – Alternative Fuel Scenario versus Base Case Maximum 24-hour $PM_{2.5}$ Dispersion Modeling Results

Condition	Change in Maximum 24-hour (µg/m^3) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-1.43	-0.49	-0.62	-1.47	-0.60	-22	-11	-12	-37	-14
100% FT (coal) aircraft and APU	-1.38	-0.47	-0.59	-1.45	-0.60	-22	-10	-11	-36	-14
100% Gate power and PCA to replace APU use	-0.58	-0.08	-0.36	-1.58	-0.20	-9	-2	-7	-40	-5
100% Electric GSE, where model available	-2.38	-0.76	-2.78	-0.49	-2.14	-37	-16	-54	-12	-51
100% LPG GSE replacing diesel GSE, where model available	-1.09	-0.23	-2.48	-0.37	-1.90	-17	-5	-48	-9	-46
100% CNG GSE replacing gasoline GSE, where model available	-0.07	-0.02	-0.04	0.35	-0.06	-1	0	-1	9	-1
100% CNG GSE replacing diesel GSE, where model available	-1.09	-0.23	-2.48	-0.37	-1.90	-17	-5	-48	-9	-46
E10 in 100% gasoline-fueled GSE	-0.31	0.00	-0.05	0.00	-0.08	-5	0	-1	0	-2
B20 in 100% diesel-fueled GSE	-0.20	0.00	-0.40	-0.03	-0.31	-3	0	-8	-1	-7
B100 in 100% diesel-fueled GSE	-0.78	0.00	-1.58	-0.13	-1.22	-12	0	-31	-3	-29
B100 in 50% diesel-fueled GSE	-0.39	0.00	-0.79	-0.07	-0.61	-6	0	-15	-2	-15
Natural gas road vehicles to replace diesel (9% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Electric road vehicles (5% of market)	-0.01	0.00	0.00	0.00	0.00	0	0	0	0	0
Electric road vehicles (10% of market)	-0.02	0.00	-0.01	0.00	0.00	0	0	0	0	0
Electric road vehicles (100% of market)	-0.18	-0.03	-0.07	-0.02	-0.01	-3	-1	-1	-1	0
E10 in 100% gasoline-fueled road vehicles	-0.06	-0.01	-0.01	-0.01	0.00	-1	0	0	0	0
B20 in diesel-fueled road vehicles (12.8% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	0.00	0.00	-0.01	0.00	0.00	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-0.01	0.00	-0.03	0.00	0.00	0	0	0	0	0

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.

Table 45 – Annual $PM_{2.5}$ Dispersion Modeling Results for Base Case and Alternative Fuel Scenarios ($\mu g/m^3$)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	1.70	2.77	1.26	2.47	2.40
100% FT (natural gas) aircraft and APU	1.34	2.53	1.09	2.02	2.06
100% FT (coal) aircraft and APU	1.35	2.54	1.10	2.03	2.06
100% Gate power and pre-conditioned air (PCA) to replace APU use	1.52	2.72	1.20	2.07	2.34
100% Electric GSE, where model available	1.19	2.46	0.78	2.33	1.17
100% LPG GSE replacing diesel GSE, where model available	1.46	2.65	0.83	2.36	1.29
100% CNG GSE replacing gasoline GSE, where model available	1.68	2.76	1.25	2.61	2.37
100% CNG GSE replacing diesel GSE, where model available	1.46	2.65	0.83	2.36	1.29
E10 in 100% gasoline-fueled GSE	1.63	2.77	1.25	2.47	2.36
B20 in 100% diesel-fueled GSE	1.65	2.77	1.19	2.46	2.22
B100 in 100% diesel-fueled GSE	1.53	2.77	0.99	2.42	1.70
B100 in 50% diesel-fueled GSE	1.61	2.77	1.12	2.45	2.05
Natural gas road vehicles to replace diesel (9% of market)	1.70	2.77	1.26	2.47	2.40
Natural gas road vehicles to replace diesel (32% of market	1.70	2.77	1.26	2.47	2.40
Natural gas road vehicles to replace diesel (100% of market)	1.70	2.77	1.26	2.47	2.40
Electric road vehicles (5% of market)	1.69	2.77	1.26	2.45	2.40
Electric road vehicles (10% of market)	1.68	2.76	1.26	2.44	2.40
Electric road vehicles (100% of market)	1.50	2.72	1.24	2.38	2.38
E10 in 100% gasoline-fueled road vehicles	1.68	2.75	1.26	2.42	2.40
B20 in diesel-fueled road vehicles (12.8% of market)	1.70	2.77	1.26	2.47	2.40
B20 in diesel-fueled road vehicles (100% of market)	1.69	2.77	1.26	2.47	2.40
B100 in diesel-fueled road vehicles (2.6% of market)	1.70	2.77	1.26	2.47	2.40
B100 in diesel-fueled road vehicles (6% of market)	1.70	2.77	1.26	2.47	2.40
B100 in diesel-fueled road vehicles (100% of market)	1.68	2.77	1.25	2.47	2.39

Note 1: Concentration represents airport contribution (does not include background) at the maximum receptor.
Note 2: 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.

Table 46 – Alternative Fuel Scenario versus Base Case Annual $PM_{2.5}$ Dispersion Modeling Results

Condition	Change in Maximum Annual (μg/m^3) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-0.36	-0.24	-0.17	-0.46	-0.34	-21	-9	-13	-18	-14
100% FT (coal) aircraft and APU	-0.35	-0.23	-0.16	-0.44	-0.34	-20	-8	-12	-18	-14
100% Gate power and PCA to replace APU use	-0.17	-0.05	-0.06	-0.41	-0.06	-10	-2	-5	-16	-3
100% Electric GSE, where model available	-0.51	-0.30	-0.48	-0.15	-1.23	-30	-11	-38	-6	-51
100% LPG GSE replacing diesel GSE, where model available	-0.24	-0.12	-0.43	-0.12	-1.11	-14	-4	-34	-5	-46
100% CNG GSE replacing gasoline GSE, where model available	-0.02	-0.01	-0.01	0.14	-0.03	-1	0	0	6	-1
100% CNG GSE replacing diesel GSE, where model available	-0.24	-0.12	-0.43	-0.12	-1.11	-14	-4	-34	-5	-46
E10 in 100% gasoline-fueled GSE	-0.07	0.00	-0.01	0.00	-0.04	-4	0	-1	0	-2
B20 in 100% diesel-fueled GSE	-0.04	0.00	-0.07	-0.01	-0.18	-3	0	-5	-1	-7
B100 in 100% diesel-fueled GSE	-0.17	0.00	-0.27	-0.05	-0.70	-10	0	-22	-2	-29
B100 in 50% diesel-fueled GSE	-0.08	0.00	-0.14	-0.03	-0.35	-5	0	-11	-1	-15
Natural gas road vehicles to replace diesel (9% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
Electric road vehicles (5% of market)	-0.01	0.00	0.00	-0.02	0.00	-1	0	0	-1	0
Electric road vehicles (10% of market)	-0.02	0.00	0.00	-0.03	0.00	-1	0	0	-1	0
Electric road vehicles (100% of market)	-0.19	-0.05	-0.02	-0.09	-0.02	-11	-2	-2	-4	-1
E10 in 100% gasoline-fueled road vehicles	-0.02	-0.02	0.00	-0.05	0.00	-1	-1	0	-2	0
B20 in diesel-fueled road vehicles (12.8% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	0.00	0.00	0.00	0.00	0.00	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-0.01	0.00	-0.01	-0.01	-0.01	-1	0	-1	0	0

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.

Table 47 – Maximum 24-hour ROI $PM_{2.5}$ Dispersion Modeling Results for Base Case and Alternative Fuel Scenarios (m)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	5,674	4,614	5,487	2,920	1,953
100% FT (natural gas) aircraft and APU	4,730	4,339	4,861	2,456	1,907
100% FT (coal) aircraft and APU	4,765	4,369	4,875	2,483	1,908
100% Gate power and pre-conditioned air (PCA) to replace APU use	5,437	4,591	5,048	2,680	1,923
100% Electric GSE, where model available	4,597	4,532	4,575	2,871	1,755
100% LPG GSE replacing diesel GSE, where model available	5,232	4,565	4,629	2,885	1,811
100% CNG GSE replacing gasoline GSE, where model available	5,650	4,613	5,457	2,945	1,949
100% CNG GSE replacing diesel GSE, where model available	5,232	4,565	4,629	2,885	1,811
E10 in 100% gasoline-fueled GSE	5,584	4,614	5,443	2,920	1,948
B20 in 100% diesel-fueled GSE	5,604	4,614	5,144	2,918	1,937
B100 in 100% diesel-fueled GSE	5,374	4,614	4,801	2,910	1,874
B100 in 50% diesel-fueled GSE	5,531	4,614	4,937	2,916	1,920
Natural gas road vehicles to replace diesel (9% of market)	5,674	4,614	5,487	2,920	1,953
Natural gas road vehicles to replace diesel (32% of market	5,674	4,614	5,487	2,920	1,953
Natural gas road vehicles to replace diesel (100% of market)	5,674	4,614	5,487	2,920	1,953
Electric road vehicles (5% of market)	5,673	4,614	5,484	2,919	1,953
Electric road vehicles (10% of market)	5,672	4,614	5,480	2,918	1,953
Electric road vehicles (100% of market)	5,649	4,614	5,423	2,899	1,952
E10 in 100% gasoline-fueled road vehicles	5,667	4,614	5,481	2,912	1,953
B20 in diesel-fueled road vehicles (12.8% of market)	5,674	4,614	5,486	2,920	1,953
B20 in diesel-fueled road vehicles (100% of market)	5,674	4,614	5,481	2,920	1,953
B100 in diesel-fueled road vehicles (2.6% of market)	5,674	4,614	5,486	2,920	1,953
B100 in diesel-fueled road vehicles (6% of market)	5,674	4,614	5,486	2,920	1,953
B100 in diesel-fueled road vehicles (100% of market)	5,671	4,614	5,462	2,920	1,953

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.

Table 48 – Alternative Fuel Scenario versus Base Case Maximum 24-hour ROI $PM_{2.5}$ Dispersion Modeling Results

Condition	Change in 24-hour Radius of Influence (m) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-944	-275	-626	-464	-46	-17	-6	-11	-16	-2
100% FT (coal) aircraft and APU	-909	-245	-612	-437	-45	-16	-5	-11	-15	-2
100% Gate power and PCA to replace APU use	-238	-23	-439	-241	-30	-4	-1	-8	-8	-2
100% Electric GSE, where model available	-1,077	-82	-912	-50	-198	-19	-2	-17	-2	-10
100% LPG GSE replacing diesel GSE, where model available	-442	-49	-858	-36	-142	-8	-1	-16	-1	-7
100% CNG GSE replacing gasoline GSE, where model available	-25	-1	-30	24	-4	0	0	-1	1	0
100% CNG GSE replacing diesel GSE, where model available	-442	-49	-858	-36	-142	-8	-1	-16	-1	-7
E10 in 100% gasoline-fueled GSE	-90	0	-44	0	-5	-2	0	-1	0	0
B20 in 100% diesel-fueled GSE	-71	0	-343	-3	-16	-1	0	-6	0	-1
B100 in 100% diesel-fueled GSE	-300	0	-686	-10	-79	-5	0	-12	0	-4
B100 in 50% diesel-fueled GSE	-144	0	-550	-5	-33	-3	0	-10	0	-2
Natural gas road vehicles to replace diesel (9% of market)	0	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	0	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	0	0	0	0	0	0	0	0	0	0
Electric road vehicles (5% of market)	-1	0	-4	-1	0	0	0	0	0	0
Electric road vehicles (10% of market)	-3	0	-7	-2	0	0	0	0	0	0
Electric road vehicles (100% of market)	-25	0	-64	-21	-1	0	0	-1	-1	0
E10 in 100% gasoline-fueled road vehicles	-7	0	-6	-8	0	0	0	0	0	0
B20 in diesel-fueled road vehicles (12.8% of market)	0	0	-1	0	0	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	-1	0	-6	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	0	0	-1	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	0	0	-2	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-3	0	-25	0	0	0	0	0	0	0

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.

Table 49 – Annual ROI $PM_{2.5}$ Dispersion Modeling Results for Base Case and Alternative Fuel Scenarios (m)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	4,968	4,952	4,012	4,018	1,988
100% FT (natural gas) aircraft and APU	3,893	4,836	3,926	3,235	1,963
100% FT (coal) aircraft and APU	3,913	4,853	3,933	3,319	1,964
100% Gate power and pre-conditioned air (PCA) to replace APU use	4,187	4,938	3,979	3,668	1,971
100% Electric GSE, where model available	3,993	4,898	3,808	3,907	1,894
100% LPG GSE replacing diesel GSE, where model available	4,544	4,926	3,829	3,934	1,921
100% CNG GSE replacing gasoline GSE, where model available	4,945	4,951	4,001	4,127	1,985
100% CNG GSE replacing diesel GSE, where model available	4,544	4,926	3,829	3,934	1,921
E10 in 100% gasoline-fueled GSE	4,876	4,952	3,999	4,018	1,985
B20 in 100% diesel-fueled GSE	4,903	4,952	3,976	4,007	1,980
B100 in 100% diesel-fueled GSE	4,694	4,952	3,894	3,983	1,951
B100 in 50% diesel-fueled GSE	4,838	4,952	3,949	3,997	1,972
Natural gas road vehicles to replace diesel (9% of market)	4,968	4,952	4,012	4,018	1,988
Natural gas road vehicles to replace diesel (32% of market	4,968	4,952	4,012	4,018	1,988
Natural gas road vehicles to replace diesel (100% of market)	4,967	4,952	4,012	4,018	1,988
Electric road vehicles (5% of market)	4,963	4,952	4,008	4,012	1,988
Electric road vehicles (10% of market)	4,958	4,952	4,004	4,006	1,988
Electric road vehicles (100% of market)	4,871	4,950	3,985	3,937	1,987
E10 in 100% gasoline-fueled road vehicles	4,960	4,951	4,005	3,982	1,988
B20 in diesel-fueled road vehicles (12.8% of market)	4,967	4,952	4,011	4,018	1,988
B20 in diesel-fueled road vehicles (100% of market)	4,963	4,952	4,004	4,018	1,988
B100 in diesel-fueled road vehicles (2.6% of market)	4,967	4,952	4,011	4,018	1,988
B100 in diesel-fueled road vehicles (6% of market)	4,967	4,952	4,010	4,018	1,988
B100 in diesel-fueled road vehicles (100% of market)	4,950	4,952	3,996	4,017	1,988

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.

Table 50 – Alternative Fuel Scenario versus Base Case Annual ROI $PM_{2.5}$ Dispersion Modeling Results

Condition	Change in Annual Radius of Influence (m) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-1,075	-116	-86	-783	-25	-22	-2	-2	-19	-1
100% FT (coal) aircraft and APU	-1,055	-99	-80	-699	-24	-21	-2	-2	-17	-1
100% Gate power and PCA to replace APU use	-781	-14	-33	-350	-17	-16	0	-1	-9	-1
100% Electric GSE, where model available	-975	-54	-204	-111	-94	-20	-1	-5	-3	-5
100% LPG GSE replacing diesel GSE, where model available	-424	-26	-183	-84	-67	-9	-1	-5	-2	-3
100% CNG GSE replacing gasoline GSE, where model available	-23	-1	-11	108	-3	0	0	0	3	0
100% CNG GSE replacing diesel GSE, where model available	-424	-26	-183	-84	-67	-9	-1	-5	-2	-3
E10 in 100% gasoline-fueled GSE	-92	0	-13	-1	-3	-2	0	0	0	0
B20 in 100% diesel-fueled GSE	-64	0	-36	-12	-7	-1	0	-1	0	0
B100 in 100% diesel-fueled GSE	-274	0	-118	-35	-37	-6	0	-3	-1	-2
B100 in 50% diesel-fueled GSE	-130	0	-63	-21	-16	-3	0	-2	-1	-1
Natural gas road vehicles to replace diesel (9% of market)	0	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	0	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	0	0	0	0	0	0	0	0	0	0
Electric road vehicles (5% of market)	-5	0	-4	-6	0	0	0	0	0	0
Electric road vehicles (10% of market)	-9	0	-8	-12	0	0	0	0	0	0
Electric road vehicles (100% of market)	-97	-2	-27	-82	-1	-2	0	-1	-2	0
E10 in 100% gasoline-fueled road vehicles	-8	-1	-8	-36	0	0	0	0	-1	0
B20 in diesel-fueled road vehicles (12.8% of market)	-1	0	-1	0	0	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	-5	0	-8	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	0	0	-1	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	-1	0	-2	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-18	0	-16	-1	0	0	0	0	0	0

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.

Table 51 – Maximum 24-hour Influence Area $PM_{2.5}$ Dispersion Modeling Results for Base Case and Alternative Fuel Scenarios (acres)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	14,322	3,647	11,515	1,390	364
100% FT (natural gas) aircraft and APU	8,431	2,773	9,407	880	278
100% FT (coal) aircraft and APU	8,686	2,854	9,554	903	278
100% Gate power and pre-conditioned air (PCA) to replace APU use	11,331	3,474	10,852	946	306
100% Electric GSE, where model available	9,038	2,912	6,645	1,251	113
100% LPG GSE replacing diesel GSE, where model available	11,722	3,307	7,119	1,287	149
100% CNG GSE replacing gasoline GSE, where model available	14,158	3,637	11,453	1,492	348
100% CNG GSE replacing diesel GSE, where model available	11,722	3,307	7,119	1,287	149
E10 in 100% gasoline-fueled GSE	13,650	3,647	11,425	1,389	348
B20 in 100% diesel-fueled GSE	13,874	3,647	10,793	1,381	324
B100 in 100% diesel-fueled GSE	12,519	3,647	8,667	1,354	221
B100 in 50% diesel-fueled GSE	13,429	3,647	10,076	1,372	289
Natural gas road vehicles to replace diesel (9% of market)	14,322	3,647	11,515	1,390	364
Natural gas road vehicles to replace diesel (32% of market	14,322	3,647	11,515	1,390	364
Natural gas road vehicles to replace diesel (100% of market)	14,322	3,646	11,515	1,390	364
Electric road vehicles (5% of market)	14,311	3,646	11,496	1,385	363
Electric road vehicles (10% of market)	14,299	3,646	11,476	1,380	363
Electric road vehicles (100% of market)	14,088	3,637	11,109	1,283	361
E10 in 100% gasoline-fueled road vehicles	14,259	3,643	11,480	1,350	363
B20 in diesel-fueled road vehicles (12.8% of market)	14,321	3,647	11,511	1,390	364
B20 in diesel-fueled road vehicles (100% of market)	14,313	3,647	11,479	1,390	363
B100 in diesel-fueled road vehicles (2.6% of market)	14,321	3,647	11,512	1,390	364
B100 in diesel-fueled road vehicles (6% of market)	14,320	3,647	11,507	1,390	364
B100 in diesel-fueled road vehicles (100% of market)	14,285	3,647	11,371	1,389	363

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.

Table 52 – Alternative Fuel Scenario versus Base Case Maximum 24-hour Influence Area $PM_{2.5}$ Dispersion Modeling Results

Condition	Change in 24-hour Influence Area (acres) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-5,891	-873	-2,109	-510	-86	-41	-24	-18	-37	-24
100% FT (coal) aircraft and APU	-5,635	-793	-1,961	-487	-85	-39	-22	-17	-35	-23
100% Gate power and PCA to replace APU use	-2,991	-172	-664	-444	-58	-21	-5	-6	-32	-16
100% Electric GSE, where model available	-5,283	-735	-4,871	-139	-251	-37	-20	-42	-10	-69
100% LPG GSE replacing diesel GSE, where model available	-2,600	-340	-4,396	-103	-215	-18	-9	-38	-7	-59
100% CNG GSE replacing gasoline GSE, where model available	-164	-9	-62	102	-16	-1	0	-1	7	-4
100% CNG GSE replacing diesel GSE, where model available	-2,600	-340	-4,396	-103	-215	-18	-9	-38	-7	-59
E10 in 100% gasoline-fueled GSE	-672	0	-91	0	-16	-5	0	-1	0	-4
B20 in 100% diesel-fueled GSE	-448	0	-722	-9	-39	-3	0	-6	-1	-11
B100 in 100% diesel-fueled GSE	-1,802	0	-2,848	-36	-142	-13	0	-25	-3	-39
B100 in 50% diesel-fueled GSE	-893	0	-1,439	-18	-74	-6	0	-12	-1	-20
Natural gas road vehicles to replace diesel (9% of market)	0	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	0	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	0	-1	-1	0	0	0	0	0	0	0
Electric road vehicles (5% of market)	-11	0	-19	-5	0	0	0	0	0	0
Electric road vehicles (10% of market)	-23	-1	-39	-10	0	0	0	0	-1	0
Electric road vehicles (100% of market)	-234	-10	-406	-107	-3	-2	0	-4	-8	-1
E10 in 100% gasoline-fueled road vehicles	-63	-4	-35	-40	0	0	0	0	-3	0
B20 in diesel-fueled road vehicles (12.8% of market)	-1	0	-5	0	0	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	-9	0	-36	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	-1	0	-4	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	-2	0	-9	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-37	0	-144	-1	-1	0	0	-1	0	0

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.

Table 53 – Annual Influence Area $PM_{2.5}$ Dispersion Modeling Results for Base Case and Alternative Fuel Scenarios (acres)

Condition	ATL	LAS	PHL	SAN	MHT
Base case	9,129	5,079	6,445	2,511	454
100% FT (natural gas) aircraft and APU	5,977	4,271	5,668	1,742	351
100% FT (coal) aircraft and APU	6,126	4,345	5,733	1,784	355
100% Gate power and pre-conditioned air (PCA) to replace APU use	7,366	4,917	6,196	1,945	407
100% Electric GSE, where model available	6,729	4,618	4,835	2,310	200
100% LPG GSE replacing diesel GSE, where model available	7,912	4,859	4,993	2,361	234
100% CNG GSE replacing gasoline GSE, where model available	9,045	5,072	6,424	2,626	428
100% CNG GSE replacing diesel GSE, where model available	7,912	4,859	4,993	2,361	234
E10 in 100% gasoline-fueled GSE	8,817	5,079	6,415	2,511	436
B20 in 100% diesel-fueled GSE	8,915	5,079	6,212	2,498	419
B100 in 100% diesel-fueled GSE	8,292	5,079	5,535	2,458	313
B100 in 50% diesel-fueled GSE	8,709	5,079	5,988	2,485	385
Natural gas road vehicles to replace diesel (9% of market)	9,128	5,079	6,445	2,511	454
Natural gas road vehicles to replace diesel (32% of market	9,128	5,079	6,445	2,511	454
Natural gas road vehicles to replace diesel (100% of market)	9,126	5,079	6,445	2,511	454
Electric road vehicles (5% of market)	9,102	5,078	6,437	2,503	454
Electric road vehicles (10% of market)	9,076	5,077	6,429	2,494	454
Electric road vehicles (100% of market)	8,600	5,056	6,285	2,334	450
E10 in 100% gasoline-fueled road vehicles	9,004	5,070	6,431	2,443	454
B20 in diesel-fueled road vehicles (12.8% of market)	9,125	5,079	6,443	2,511	454
B20 in diesel-fueled road vehicles (100% of market)	9,103	5,079	6,430	2,511	454
B100 in diesel-fueled road vehicles (2.6% of market)	9,126	5,079	6,444	2,511	454
B100 in diesel-fueled road vehicles (6% of market)	9,122	5,079	6,442	2,511	454
B100 in diesel-fueled road vehicles (100% of market)	9,027	5,079	6,387	2,509	453

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.

Table 54 – Alternative Fuel Scenario versus Base Case Annual Influence Area $PM_{2.5}$ Dispersion Modeling Results

Condition	Change in Annual Influence Area (acres) from Base Case					Percent Change from Base Case				
	ATL	LAS	PHL	SAN	MHT	ATL	LAS	PHL	SAN	MHT
100% FT (natural gas) aircraft and APU	-3,151	-808	-777	-769	-104	-35	-16	-12	-31	-23
100% FT (coal) aircraft and APU	-3,003	-734	-713	-728	-99	-33	-14	-11	-29	-22
100% Gate power and PCA to replace APU use	-1,762	-163	-249	-566	-47	-19	-3	-4	-23	-10
100% Electric GSE, where model available	-2,400	-462	-1,610	-202	-254	-26	-9	-25	-8	-56
100% LPG GSE replacing diesel GSE, where model available	-1,216	-220	-1,453	-151	-220	-13	-4	-23	-6	-48
100% CNG GSE replacing gasoline GSE, where model available	-84	-7	-21	114	-27	-1	0	0	5	-6
100% CNG GSE replacing diesel GSE, where model available	-1,216	-220	-1,453	-151	-220	-13	-4	-23	-6	-48
E10 in 100% gasoline-fueled GSE	-312	0	-30	-1	-18	-3	0	0	0	-4
B20 in 100% diesel-fueled GSE	-214	0	-233	-13	-36	-2	0	-4	-1	-8
B100 in 100% diesel-fueled GSE	-836	0	-910	-54	-141	-9	0	-14	-2	-31
B100 in 50% diesel-fueled GSE	-420	0	-458	-26	-70	-5	0	-7	-1	-15
Natural gas road vehicles to replace diesel (9% of market)	-1	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (32% of market	-1	0	0	0	0	0	0	0	0	0
Natural gas road vehicles to replace diesel (100% of market)	-3	0	0	0	0	0	0	0	0	0
Electric road vehicles (5% of market)	-27	-1	-8	-8	0	0	0	0	0	0
Electric road vehicles (10% of market)	-53	-2	-16	-17	0	-1	0	0	-1	0
Electric road vehicles (100% of market)	-529	-24	-160	-177	-5	-6	0	-2	-7	-1
E10 in 100% gasoline-fueled road vehicles	-125	-9	-15	-68	0	-1	0	0	-3	0
B20 in diesel-fueled road vehicles (12.8% of market)	-4	0	-2	0	0	0	0	0	0	0
B20 in diesel-fueled road vehicles (100% of market)	-26	0	-15	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (2.6% of market)	-3	0	-2	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (6% of market)	-7	0	-4	0	0	0	0	0	0	0
B100 in diesel-fueled road vehicles (100% of market)	-102	0	-59	-2	-2	-1	0	-1	0	0

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.

Table 55 – Annual $PM_{2.5}$ Emissions Inventory (kg) for Turboprop and Piston-engine Aircraft

Condition	Scenario	ATL	LAS	PHL	SAN	MHT
Turboprop	Base case	3,337	985	4,119	1,266	2,189
	FTG1	1,684	499	2,094	642	1,107
Piston-engine	Base case	2.3	0.6	289	1.3	2.68
	AGUL1	0.06	0.02	7.1	0.03	0.07

APPENDIX F: GUIDANCE DOCUMENT

> *Note: The spreadsheet tool referenced herein is available for download on the publication summary page on the TRB website. Access to this page is provided via the "ACRP Web-Only Document 13 Web Page" link on this document's bookmark menu.*

This Guidance Document has been written as a key output from the ACRP 02-23 project *Alternative Fuels as a means to reduce $PM_{2.5}$ Emissions at Airports*, Principal Investigators: Dr. Hazel Peace and Damon Fordham of PPC/AEA with contributing authors Jamie Beevor, Dr. Mark Broomfield, Dr. John Norris and Dr. Brian Underwood; Mike Kenney, Mike Ratte and Paul Sanford of KB Environmental Sciences Inc.; Dr. Mary E. Johnson and David L. Stanley of Purdue University; Mary Vigilante of Synergy Consultants Inc.; and Richard Altman.

BACKGROUND

The U.S. National Ambient Air Quality Standards (NAAQS) for fine particulate matter with a diameter of less than 2.5 micrometers ($PM_{2.5}$) are set primarily for the protection of public health. The current 24-hour NAAQS for $PM_{2.5}$ is 35 $\mu g/m^3$ and the annual standard is 15 $\mu g/m^3$. Over 50 commercial airports in the U.S. are in areas that are classed as $PM_{2.5}$ "non-attainment" (i.e., in breach of the NAAQS). Proposed improvement projects at Los Angeles International Airport and Philadelphia International Airport are facing agency review because of the potential impacts to local and regional $PM_{2.5}$ air quality. Other airports around the country (e.g., Chicago O'Hare International, Seattle-Tacoma International, and George Bush Intercontinental/Houston) have all experienced similar public concerns about the potential health effects associated with the combustion of jet fuel, principally due to emissions-related to particulate matter. It is anticipated that expansion of other airports to address capacity needs will face increased pressure to consider particulate matter impacts and emissions of related local pollutants. One of the ways in which airports can assist in reducing $PM_{2.5}$ impacts is by increasing the availability and use of alternative fuels.

This guidance has been produced as an outcome of the ACRP 02-23 research project and is based on the project's findings. The ARCP 02-23 project was undertaken from July 2010 to December 2011. The ACRP 02-23 project's aim was 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. The results were 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.

This Guidance Document provides airport operators, and others, with an understanding of the relative potential benefits of alternative fuels as a means of reducing the impacts of $PM_{2.5}$ emissions and aims to support decision-making by providing technical supporting material. While airports are the primary audience for this document, other non-airport stakeholders, particularly airlines, fuel providers, equipment manufacturers, and ground support providers (e.g., airside operations, passenger transportation operators, and construction equipment operators) may benefit from using this guidance.

LEVEL OF ANALYSIS – A TIERED APPROACH

Different users of this guidance will wish to approach the selection of alternative fuels at different levels of detail. Therefore, this guidance is split into three tiers:

- **Tier 1** is high level guidance based on a number of key criteria, which is suitable for airport executives, senior managers, and their clients/service providers, and will help establish key messages as part of stakeholder engagement.
- **Tier 2** presents a spreadsheet tool based on the emission results from the five case study airports analyzed in the ACRP 02-23 project. The tool allows users to combine the impacts of different alternative fuel scenarios at those airports and to alter penetration factors to enable them to understand the different source and alternative fuel impacts. This tool is aimed at airport environmental managers.
- **Tier 3** refers the reader to the ACRP 02-23 Final Report and is intended for those who wish to undertake a detailed study of their own airport following the methodology used in the ACRP 02-23 project.

The ACRP 02-23 Final Report provides more detail on the information presented in each tier of this guidance.

TIER 1

The primary purpose of the Tier 1 guidance is to help airports to undertaken a high level assessment of the suitability of various alternative fuels as substitutes for conventional fuels for a particular emission source.

Each combination of alternative fuel and emission source was rated in the ACRP 02-23 project in terms of key criteria. The definitions for each of the criterion and their ratings are shown in Table 56. After Table 56 each of the major airport emission sources—jet-fueled aircraft, AvGas-fueled aircraft (i.e., piston-engine aircraft), auxiliary power units (APUs), ground support equipment (GSE), and road vehicles—are briefly discussed, followed in turn by a table highlighting each alternative fuel and the ratings that were assigned for each of the key criteria in the ACRP 02-23 project. The information in these tables will allow readers to assess which alternative fuels may be appropriate for consideration at their airports.

The ACRP 02-23 project determined that other airport sources of $PM_{2.5}$ were generally small in comparison to those sources listed above, at least for the case study airports analyzed. Consequently, other sources are not included in this guidance. However, some airports may have other equipment or machinery that does represent a significant emissions source, such as oil or solid-fueled power and/or heat generation. These sources will need further consideration on a case-by-case basis. Further detail is provided in the ACRP 02-23 Final Report.

Table 56 – Alternative Fuels – Criteria and Definitions

Criterion	Definition	Rating
Change in $PM_{2.5}$ emissions (H, M, L)	The relative decrease in emissions compared with the dominant existing fuel/engine (or vehicle)	H = >75% reduction M = Between 25% and 75% reduction L = <25% reduction
Availability of fuel (H, M, L)	Is the fuel currently available?	H = Widespread availability of fuel/blend in many states, though some regional variability M = Frequently available, but not at all sites/locations and would often require additional infrastructure (e.g., tanks) L = Limited/not readily available
Availability of new vehicles (H, M, L)	Are vehicles that can use this fuel currently available or are they likely to be available in the short-term? It should be noted that model availability depends on purpose	H = Many model types readily available for this fuel type and many being used M = Many model types available that can use this fuel, though not universal L = Not many models available (if any) that can use this fuel
Cost to convert existing vehicles (H,M,L)	How much is it likely to cost to convert a typical vehicle?	H = >$20,000 M = Between $200 and $20,000 L = <$200 N/A = no cost associated (i.e., for drop-in fuels).
Drop-in fuel for existing vehicle? (Y/N)	Can the fuel be used in existing vehicles with no modification?	Y/N or N/A
GHG life-cycle emissions (H, M, L)	Greenhouse gas (GHG) emissions of the alternative fuel relative to the primary conventional fuel. This figure includes the fuel processing (i.e., “well to wheel”) emissions	H = >90% of conventional fuel M = Between 40% and 90% of conventional fuel L = <40% of conventional fuel
Emission data source reliability (H, M, L)	Is the source of the proposed emission factors based on reliable data?	H = Widely tested, many high-quality (government or referred journal) published studies with similar results for a range of vehicles M = Published studies, but limited to one or two vehicles L = No specific data, assumptions based on similar source (e.g., road vehicle for GSE) or based on calculations
Cost of fuel compared with conventional (H, E, L)	This is the marginal increase in fuel cost compared with the dominant existing fuel	H = >125% of conventional fuel E = Equivalent price to conventional fuel – between 75% and 125% of conventional fuel L = <75% of conventional fuel (N/A where no data on cost are available. Variable and N/A assume worst case, high cost)
Cost of vehicles compared with conventional (H, M, L)	This is the marginal increase in vehicle cost compared with the dominant existing vehicle type	H = > 200% M = between 110% and 200% L = <110% N/A = no additional cost (i.e., for drop-in fuels).

Criterion	Definition	Rating
Additional infrastructure needed (H, M, L)	What additional infrastructure is needed for the fuel to be used?	H = Additional equipment such as compressors, high pressure buffers and tanks needed M = Additional tanks, similar to those already in existence, would be needed (e.g., for different blends) L = Assumes that diesel, electricity and gasoline are readily available on, or near, the site N/A = no additional cost associated.
Warranty validity issue (Y/N)	Could the use of this fuel result in vehicle/engine warranty being invalidated?	Y/N

Note that "vehicle" is used here to refer to aircraft, APU, GSE and road vehicles

Jet-fueled Aircraft

ASTM International has approved an alternative jet fuel specification in annexes to ASTM D7566 for Fischer-Tropsch (FT) and hydroprocessed renewable jet (HRJ) fuels blended with at least 50% conventional jet fuel. This means that, in theory, these fuels can now be produced and sold as a "drop-in" fuel for aircraft (i.e., no modifications are required to the aircraft to use this fuel). However, current availability is limited. Particulate matter emission reduction data for HRJ fuels were not finalized at the time of writing, so they are not included here. However, it is likely that emission reductions will be similar to those for FT fuels. With 50/50 FT blended fuels, total particulate matter emission reductions are in the region of 50% for aircraft engines and APUs. The cost of FT and HRJ fuels are currently high compared to costs of conventional jet fuel. However, as commercial productivity and demand increase, the cost is likely to reduce. Other considerations are shown in Table 57.

Table 57 – Jet-fueled Aircraft Alternative Fuels

Criterion	Change $PM_{2.5}$ emissions (H, M, L)	Availability of fuel (H, M, L)	Availability of new vehicles (H, M, L)	Cost to convert existing vehicles (H,M,L)	Drop-in fuel for existing vehicle? (Y/N or N/A)	GHG life-cycle emissions (H, M, L)	Emission data source reliability (H, M, L)	Cost of fuel compared with conventional (H, E, L)	Cost of vehicles compared with conventional (H, M, L)	Additional infrastructure needed (H, M, L)	Warranty validity issue (Y/N or N/A)
Low-sulfur Jet-A for aircraft	L	L	H	N/A	Y	H	L	E	N/A	L	N
FT (natural gas) aircraft	M	L	H	N/A	Y	H	M	H	N/A	L	N
FT (coal) aircraft	M	L	H	N/A	Y	H	M	H	N/A	L	N
FT (biomass) aircraft	M	L	H	N/A	Y	H	L	H	N/A	L	N
HRJ (biomass) aircraft	M	L	H	N/A	Y	H	L	H	N/A	L	N

AvGas-Fueled Aircraft (Piston-engine Aircraft)

While alternative AvGas fuel not is yet commercially available in the U.S., it could be in the future. Compared with 100LL (the AvGas used in the U.S.), 91/96UL produces emission reductions in the region of 90% for piston-engine aircraft. Other considerations are shown in Table 58.

Table 58 – Piston-engine Aircraft Alternative Fuels

Criterion	Change $PM_{2.5}$ emissions (H, M, L)	Availability of fuel (H, M, L)	Availability of new vehicles (H, M, L)	Cost to convert existing vehicles (H,M,L)	Drop-in fuel for existing vehicle? (Y/N or N/A)	GHG life-cycle emissions (H, M, L)	Emission data source reliability (H, M, L)	Cost of fuel compared with conventional (H, E, L)	Cost of vehicles compared with conventional (H, M, L)	Additional infrastructure needed (H, M, L)	Warranty validity issue (Y/N or N/A)
91/96UL AvGas for piston-engine aircraft	H	L	L	L	Y	H	M	E	N/A	M	Y

APU

APU emissions can be reduced in two ways. First, by reducing APU use (e.g., by providing and encouraging use of alternatives, such as fixed electric ground power (FEGP) and pre-conditioned air (PCA)). Second, by using alternative jet fuel instead of conventional fuels (refer to Jet-fueled Aircraft, above). FEGP and PCA are likely to require high up-front investment, although grants are available through the Federal Aviation Administration's (FAA) Voluntary Airport Low Emissions (VALE) program. Other considerations are shown in Table 59.

Table 59 – APU Alternative Fuels

Criterion	Change $PM_{2.5}$ emissions (H, M, L)	Availability of fuel (H, M, L)	Availability of new vehicles (H, M, L)	Cost to convert existing vehicles (H,M,L)	Drop-in fuel for existing vehicle? (Y/N or N/A)	GHG life-cycle emissions (H, M, L)	Emission data source reliability (H, M, L)	Cost of fuel compared with conventional (H, E, L)	Cost of vehicles compared with conventional (H, M, L)	Additional infrastructure needed (H, M, L)	Warranty validity issue (Y/N or N/A)
FT (natural gas) APU	M	L	H	N/A	Y	H	L	H	N/A	L	N
FT (coal) APU	M	L	H	N/A	Y	H	M	H	N/A	L	N
FT (biomass) APU	M	L	H	N/A	Y	H	L	H	N/A	L	N
HRJ (biomass) APU	M	L	H	N/A	Y	H	L	H	N/A	L	Y
Low-sulfur Jet-A for APU	L	L	H	L	Y	H	L	E	N/A	L	N
Electricity to replace some APU use	M	H	H	N/A	Y	V	H	V	N/A	H	N

GSE

Grants for purchasing alternative-fueled GSE are available through the FAA's VALE program. In addition, drop-in fuels such as biodiesel (B20) and ethanol (E10) can be used to replace diesel and gasoline, respectively, as a drop-in fuel. However, the greatest $PM_{2.5}$ emission reductions are gained when diesel GSE are replaced by (in increasing order) gasoline, CNG, LPG or electric GSE, where an appropriate alternatively fueled GSE exists. The costs of alternative fuels for GSE are typically either equivalent or slightly higher when compared to the conventional fuel, with the exception of the high-biofuel blends (e.g., E85 and B100). The high-biofuel blends may also create problems in terms of warranty invalidation for GSE. Other considerations are shown in Table 60.

While retrofit technology is not the subject of this report, it could be advantageous to fit equipment (e.g., particulate matter traps) to existing GSE diesel engines given the uncertainties of particulate matter emissions and to be cost-effective. Where vehicle replacement is an option, electric GSE is better when compared with other alternative fuels in terms of reducing directly emitted particulate matter (U.S. FAA, 2010a). Around the world, electric vehicles are available as replacements for baggage tugs and belt loaders. A few other specialist airside electric vehicles have been trialed, and there are a few makes of electric aircraft push-back tugs. However, their relatively modest capacity suggests they would not be very flexible and unable to deal with larger aircraft.

Table 60 – GSE Alternative Fuels

Criterion	Change $PM_{2.5}$ emissions (H, M, L)	Availability of fuel (H, M, L)	Availability of new vehicles (H, M, L)	Cost to convert existing vehicles (H,M,L)	Drop-in fuel for existing vehicle? (Y/N or N/A)	GHG life-cycle emissions (H, M, L)	Emission data source reliability (H, M, L)	Cost of fuel compared with conventional (H, E, L)	Cost of vehicles compared with conventional (H, M, L)	Additional infrastructure needed (H, M, L)	Warranty validity issue (Y/N or N/A)
Electric GSE	H	H	H	N/A	N	V	H	V	H	L	N
LPG GSE replacing gasoline GSE	L	H	L	L	N	H	H	H	M	M	Y
LPG GSE replacing diesel GSE	H	H	L	H	N	H	H	H	M	M	Y
CNG GSE replacing gasoline GSE	M	H	L	M	N	H	H	L	M	H	Y
CNG GSE replacing diesel GSE	H	H	L	H	N	H	H	L	M	H	Y
Low-sulfur diesel GSE	L	H	H	N/A	Y	H	L	E	N/A	L	N
E5 in gasoline-fueled GSE	L	H	M	N/A	Y	H	L	E	N/A	N/A	N
E10 in gasoline-fueled GSE	M	H	M	N/A	Y	H	L	E	N/A	N/A	N
E15 in gasoline-fueled GSE	M	L	L	L	N	H	L	N/A	L	L	Y
E85 in gasoline-fueled GSE	L	M	L	L	N	M	L	H	L	L	Y
B5 in diesel-fueled GSE	L	H	H	N/A	Y	H	L	E	N/A	N/A	N
B10 in diesel-fueled GSE	L	L	M	L	N	H	L	N/A	L	M	Y
B15 in diesel-fueled GSE	L	L	M	L	N	H	L	N/A	L	M	Y
B20 in diesel-fueled GSE	L	M	M	L	N	H	L	E	L	L	Y
B100 in diesel-fueled GSE	M	M	L	M	N	M	L	H	L	L	Y

Road Vehicles

Drop-in fuels, such as B20 and E10, can be used to replace diesel and gasoline respectively. However, the greatest $PM_{2.5}$ emission reductions are gained when diesel vehicles are replaced by (in increasing order) gasoline, CNG, LPG or electric vehicles. The cost of alternative fuels for road vehicles are typically either equivalent or slightly higher than the convention fuel, with the exception of the high-biofuel blends (e.g., E85 and B100) which are more costly. The high-biofuel blends may also create problems in terms of warranty invalidation for road vehicles. Although there is a limit to the number of road vehicles that airports can influence beyond their own fleet, mechanisms such as structured parking lot charges and taxi licensing can help to encourage alternative fuel use in road vehicles. Other considerations are shown in Table 61.

Table 61 – Road Vehicle Alternative Fuels

Criterion	Change $PM_{2.5}$ emissions (H, M, L)	Availability of fuel (H, M, L)	Availability of new vehicles (H, M, L)	Cost to convert existing vehicles (H,M,L)	Drop-in fuel for existing vehicle? (Y/N or N/A)	GHG life-cycle emissions (H, M, L)	Emission data source reliability (H, M, L)	Cost of fuel compared with conventional (H, E, L)	Cost of vehicles compared with conventional (H, M, L)	Additional infrastructure needed (H, M, L)	Warranty validity issue (Y/N or N/A)
Low-sulfur diesel road vehicles	N/A	N/A	N/A	N/A	Y	N/A	N/A	E	N/A	N/A	N
Natural gas road vehicles to replace diesel	H	H	M	M	N	H	L	L	M	H	N
Electric road vehicles	H	H	L	N/A	N	V	H	V	H	L	N
E5 in gasoline-fueled road vehicles	L	H	H	N/A	Y	H	L	E	N/A	N/A	N
E10 in gasoline-fueled road vehicles	M	H	H	N/A	Y	H	M	E	N/A	N/A	N
E15 in gasoline-fueled road vehicles	M	L	H	L	N	H	L	N/A	L	L	Y
E85 in gasoline-fueled road vehicles	L	M	H	L	N	M	L	H	L	L	Y
B5 in diesel-fueled road vehicles	L	H	H	N/A	Y	H	H	E	N/A	N/A	N
B10 in diesel-fueled road vehicles	L	L	H	L	N	H	H	N/A	N/A	M	Y
B15 in diesel-fueled road vehicles	L	L	H	L	N	H	H	N/A	N/A	M	Y
B20 in diesel-fueled road vehicles	L	M	H	L	N	H	H	E	N/A	L	Y
B100 in diesel-fueled road vehicles	M	M	L	M	N	M	H	H	M	L	Y

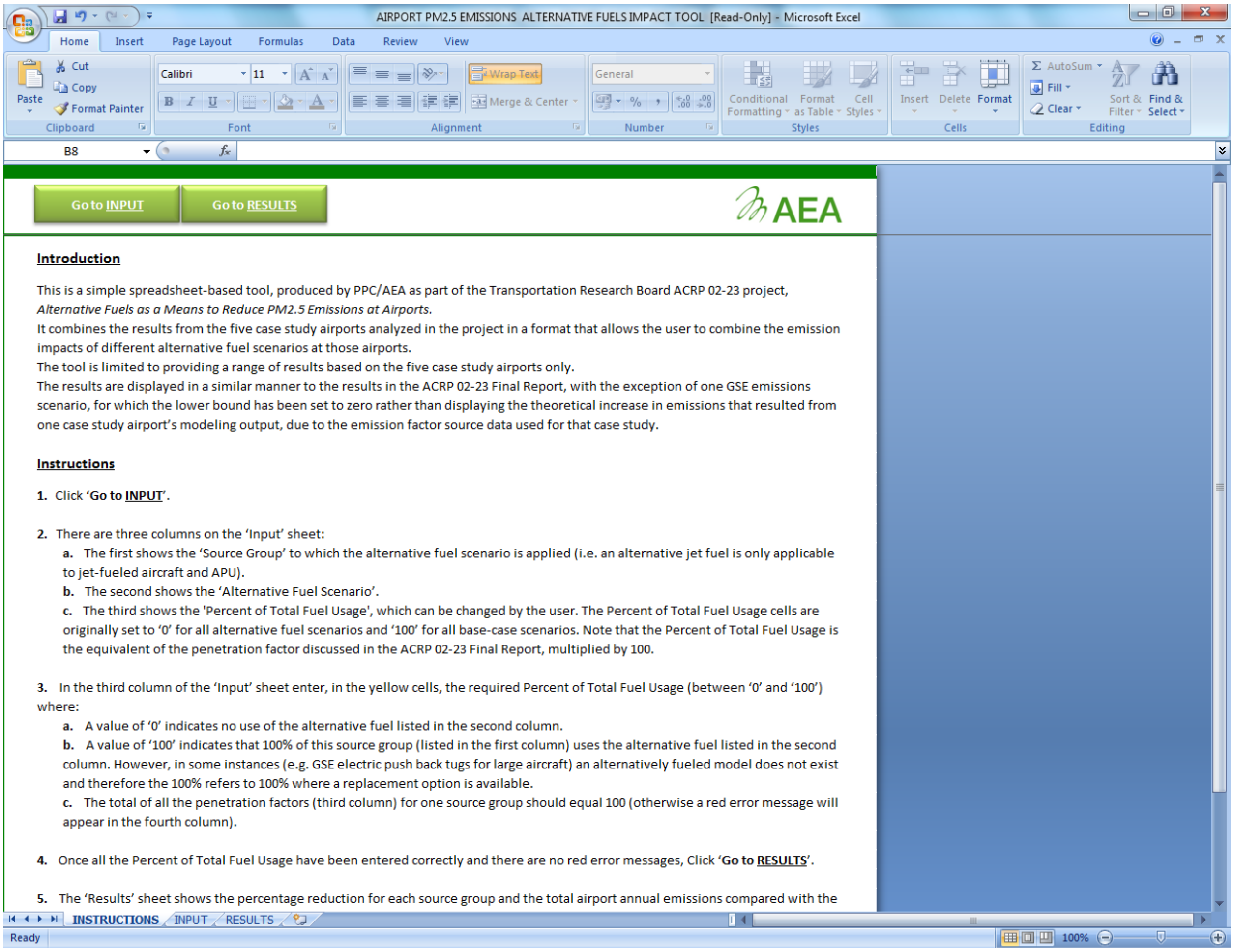
TIER 2

Tier 2 is a spreadsheet-based tool "*AIRPORT PM2.5 EMISSIONS ALTERNATIVE FUELS IMPACT TOOL.xlsx*." It combines the results from the five case study airports analyzed in the ACRP 02-23 project in a format that allows the user to combine the emission impacts of different alternative fuel scenarios at those airports. The tool is limited to providing a range of results based on the five case study airports only. The results are displayed in a similar format to the results in the ACRP 02-23 Final Report, with the exception of one GSE emissions scenario, for which the lower bound has been set to zero rather than displaying the theoretical increase in emissions that resulted from one case study airport's modeling output, due to the emission factor source data used for that case study. Instructions for use are below, and are also included in the spreadsheet tool itself.

Instructions

Open the file "*AIRPORT PM2.5 EMISSIONS ALTERNATIVE FUELS IMPACT TOOL.xlsx*."

1. The tool should open with the "*Instructions*" sheet (Figure 22) for the user's review. These are reproduced below.



Introduction

This is a simple spreadsheet-based tool, produced by PPC/AEA as part of the Transportation Research Board ACRP 02-23 project, *Alternative Fuels as a Means to Reduce PM2.5 Emissions at Airports.*
It combines the results from the five case study airports analyzed in the project in a format that allows the user to combine the emission impacts of different alternative fuel scenarios at those airports.
The tool is limited to providing a range of results based on the five case study airports only.
The results are displayed in a similar manner to the results in the ACRP 02-23 Final Report, with the exception of one GSE emissions scenario, for which the lower bound has been set to zero rather than displaying the theoretical increase in emissions that resulted from one case study airport's modeling output, due to the emission factor source data used for that case study.

Instructions

1. Click '**Go to INPUT**'.

2. There are three columns on the 'Input' sheet:
   a. The first shows the 'Source Group' to which the alternative fuel scenario is applied (i.e. an alternative jet fuel is only applicable to jet-fueled aircraft and APU).
   b. The second shows the 'Alternative Fuel Scenario'.
   c. The third shows the 'Percent of Total Fuel Usage', which can be changed by the user. The Percent of Total Fuel Usage cells are originally set to '0' for all alternative fuel scenarios and '100' for all base-case scenarios. Note that the Percent of Total Fuel Usage is the equivalent of the penetration factor discussed in the ACRP 02-23 Final Report, multiplied by 100.

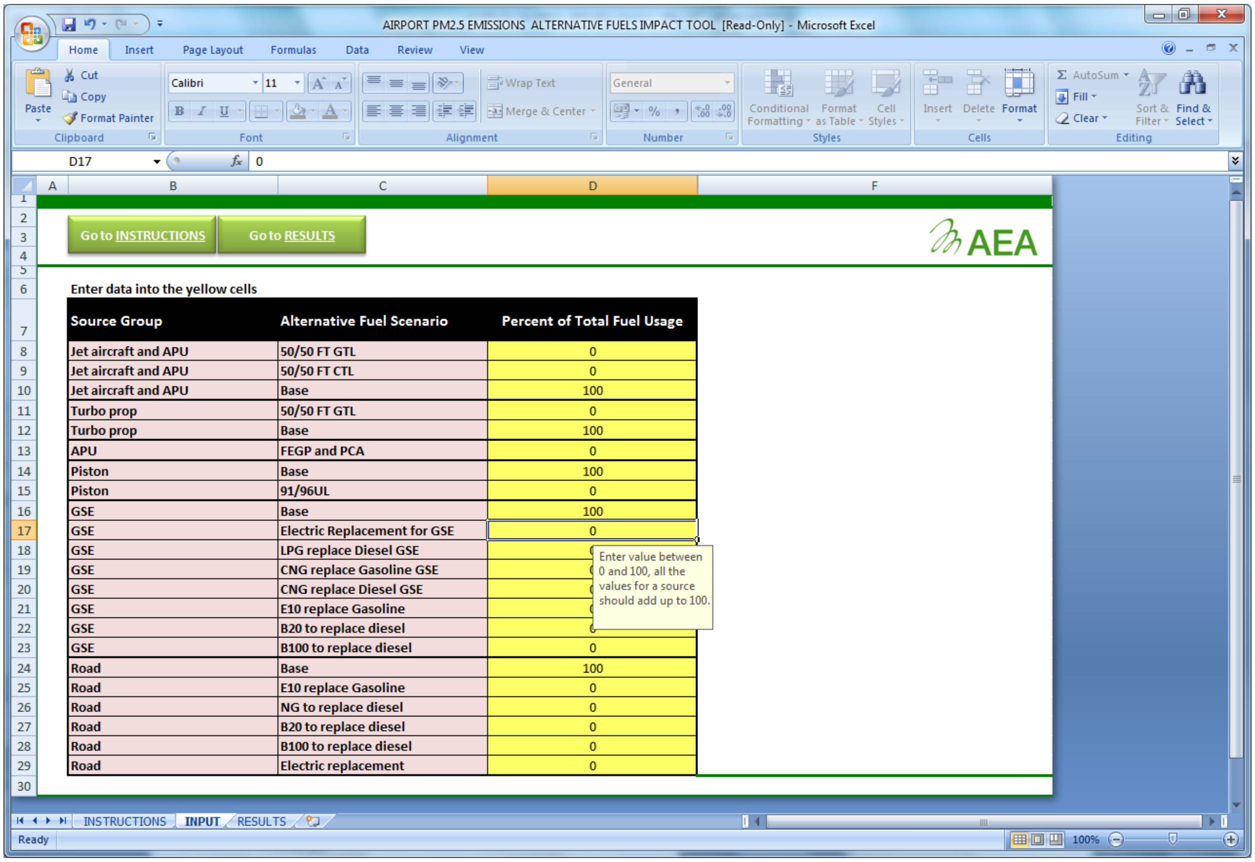
3. In the third column of the 'Input' sheet enter, in the yellow cells, the required Percent of Total Fuel Usage (between '0' and '100') where:
   a. A value of '0' indicates no use of the alternative fuel listed in the second column.
   b. A value of '100' indicates that 100% of this source group (listed in the first column) uses the alternative fuel listed in the second column. However, in some instances (e.g. GSE electric push back tugs for large aircraft) an alternatively fueled model does not exist and therefore the 100% refers to 100% where a replacement option is available.
   c. The total of all the penetration factors (third column) for one source group should equal 100 (otherwise a red error message will appear in the fourth column).

4. Once all the Percent of Total Fuel Usage have been entered correctly and there are no red error messages, Click '**Go to RESULTS**'.

5. The 'Results' sheet shows the percentage reduction for each source group and the total airport annual emissions compared with the

Figure 22 – Tool Instruction Sheet

2. Click “Go to INPUT” (Figure 23).
3. There are three columns on the “Input” sheet:
    a. The first shows the “Source Group” to which the alternative fuel scenario is applied (i.e., an alternative jet fuel is only applicable to jet-fueled aircraft and APU).
    b. The second shows the “alternative fuel scenario.”
    c. The third column shows the “Percent of Total Fuel Usage,” which can be changed by the user. The Percent of Total Fuel Usage are originally set to “0” for all alternative fuel scenarios and “100” for all base case scenarios. Note that the Percent of Total Fuel Usage is the equivalent of the penetration factor discussed in the ACRP 02-23 Final Report, multiplied by 100.



Enter data into the yellow cells

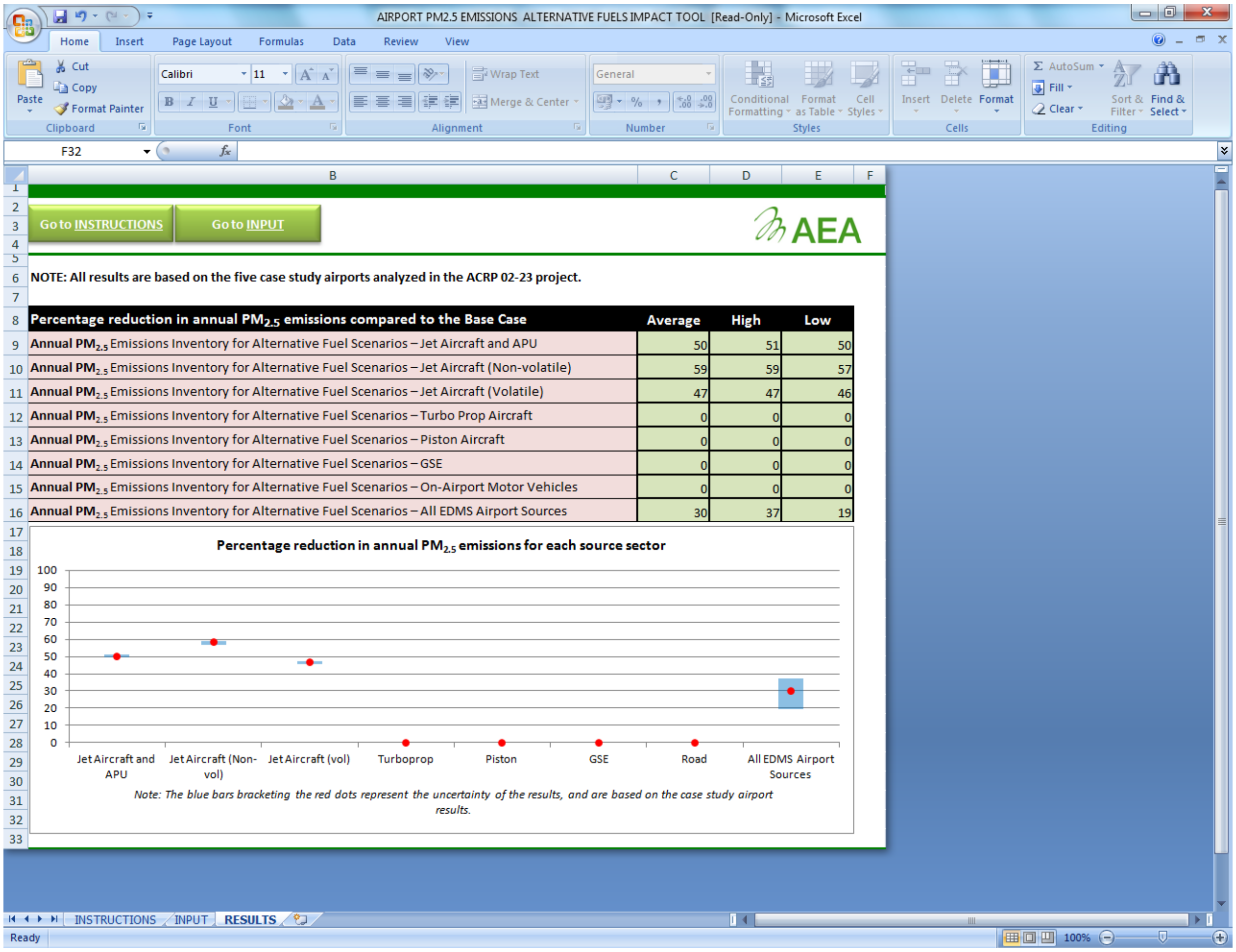
Source Group	Alternative Fuel Scenario	Percent of Total Fuel Usage
Jet aircraft and APU	50/50 FT GTL	0
Jet aircraft and APU	50/50 FT CTL	0
Jet aircraft and APU	Base	100
Turbo prop	50/50 FT GTL	0
Turbo prop	Base	100
APU	FEGP and PCA	0
Piston	Base	100
Piston	91/96UL	0
GSE	Base	100
GSE	Electric Replacement for GSE	0
GSE	LPG replace Diesel GSE	0
GSE	CNG replace Gasoline GSE	0
GSE	CNG replace Diesel GSE	0
GSE	E10 replace Gasoline	0
GSE	B20 to replace diesel	0
GSE	B100 to replace diesel	0
Road	Base	100
Road	E10 replace Gasoline	0
Road	NG to replace diesel	0
Road	B20 to replace diesel	0
Road	B100 to replace diesel	0
Road	Electric replacement	0

Enter value between 0 and 100, all the values for a source should add up to 100.

Figure 23 – Tool Input Sheet

4. In the third column of the “Input” sheet enter, in the yellow cells, the required Percent of Total Fuel Usage (between “0” and “100”) where:
    a. A value of “0” indicates no use of the alternative fuel listed in the second column.
    b. A value of “100” indicates that 100% of this source group (listed in the first column) use the alternative fuel listed in the second column. However, in some instances (e.g. GSE electric push-back tugs for large aircraft), an alternatively fueled model does not exist and therefore the 100% refers to 100% where a replacement option is available.
    c. The total of all the penetration factors (third column) for one source group should equal 100 (otherwise a red error message will appear in the fourth column).

5. Once all the Percent of Total Fuel Usage have been entered correctly and there are no red error messages, click "Go to RESULTS" (Figure 24).
6. The "Results" sheet shows the percentage reduction for each source group and the total airport annual emissions compared with the base case. This is presented as a range of values based on the five case study airports. The results are shown in tabular and graphical formats.
7. Results can be saved by using the "File > Save As" function.



NOTE: All results are based on the five case study airports analyzed in the ACRP 02-23 project.

Percentage reduction in annual $PM_{2.5}$ emissions compared to the Base Case	Average	High	Low
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – Jet Aircraft and APU	50	51	50
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – Jet Aircraft (Non-volatile)	59	59	57
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – Jet Aircraft (Volatile)	47	47	46
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – Turbo Prop Aircraft	0	0	0
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – Piston Aircraft	0	0	0
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – GSE	0	0	0
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – On-Airport Motor Vehicles	0	0	0
Annual $PM_{2.5}$ Emissions Inventory for Alternative Fuel Scenarios – All EDMS Airport Sources	30	37	19

Note: The blue bars bracketing the red dots represent the uncertainty of the results, and are based on the case study airport results.

Figure 24 – Tool Results Sheet

TIER 3

In some instances, an individual airport may wish to undertake its own, more-detailed study. The types of data that airports would need to collate to generate a base case emissions inventory and undertake dispersion modeling are summarized in Table 62. In addition, Appendix A of the Emissions and Dispersion Modeling System (EDMS) user manual (U.S. FAA, 2009a) provides an overview and screen shots of the data needed and how to enter them into EDMS. Meteorological data would need to be obtained in AERMOD format, and the EDMS manual lists where those data can be obtained. A flow chart summarizing the methodology is shown in Figure 25. To generate the alternative fuel scenarios, analysts should refer to the ACRP 02-23 Final Report, and in particular, to the methodology described in Chapter 5 and Appendix D. For most alternative-fuel scenarios, alternative fuel emission factors can be applied. However, some scenarios for GSE and road vehicles cannot be directly scaled. For those GSE scenarios that cannot be scaled, alternative fuel scenarios can be investigated via EDMS (refer to the user manual (U.S. FAA, 2009 and 2009a)). Stationary source alternative fuel scenarios can also be investigated via the EDMS interface. For road vehicle scenarios that cannot be scaled the alternative fuel scenarios can be investigated using the MOBILE model (or potentially the MOVES model), and, again, the user manuals for the relevant models should be consulted.

Table 62 – Typical Data Used in $PM_{2.5}$ Emission Inventories

Source Category	Data
Aircraft	LTO by aircraft type and engine type Taxi-in, taxi-out, delay times (aircraft time in mode) Profiles of quarter hour, daily and monthly activity levels Runway and taxiway assignments and coordinates Terminal/gate assignments and locations
Ground support equipment (GSE)	Number and type by aircraft type Fuel type Size and load Operating times
Auxiliary power units (APU)	Percent of gates with fixed power units Percent of gates with fixed pre-conditioned air
Road vehicles	Location, by segment Vehicle fleet mix by segment Roadway traffic volume by segment Average speed Emission factors (generated using either MOBILE6.2 or EMFAC2007 models)
Parking facility	Location by parking lot Vehicle fleet mix by parking lot Traffic volume by parking lot Travel distance Idle time
Stationary sources	Type and location Fuel type and quantity Stack height and diameter Exhaust temperature and velocity

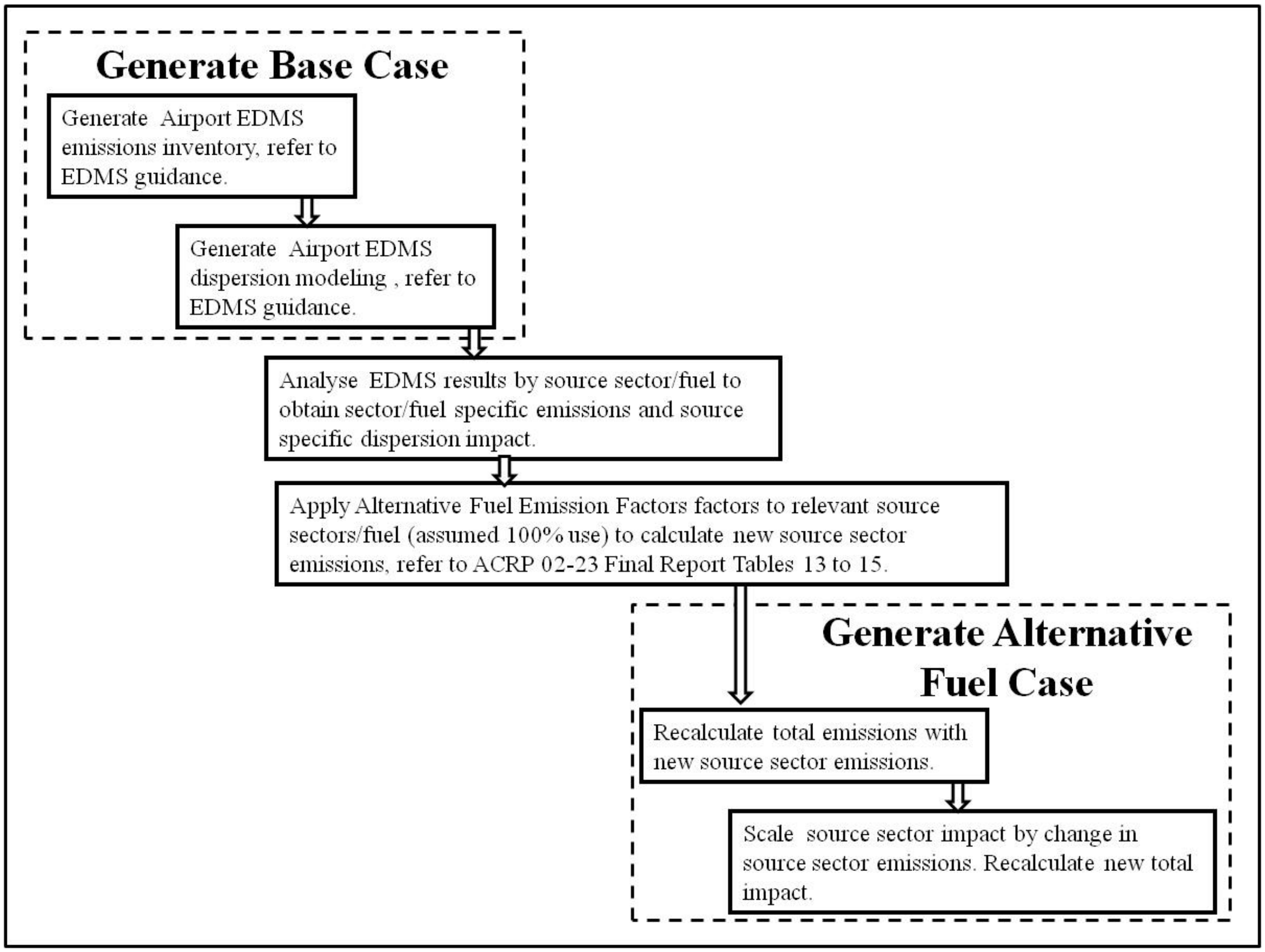


Figure 25 – Methodology Flow Chart