

Scaling Air Quality Effects from Alternative Jet Fuel in Aircraft and Ground Support Equipment

by

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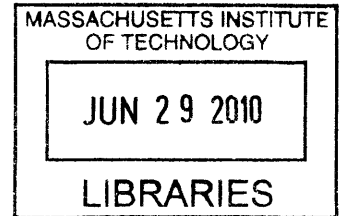
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Abstract

Many of the nation's largest airports, including Los Angeles International Airport, the Hartsfield-Jackson Atlanta International Airport, Chicago O'Hare International Airport and Washington Dulles International Airport are located within areas designated by the EPA as having ambient particulate matter concentrations that exceed National Ambient Air Quality standards. When inhaled, fine particulate matter can enter the blood stream from the lungs and increase the risk of illness and premature mortality. This thesis examines the potential of two jet fuel types, ultra low sulfur jet fuel and synthetic paraffinic kerosene, to reduce aviation's contribution to ambient particulate matter concentrations.

Scaling factors were developed for airport criteria pollutant emissions to model alternative jet fuels in aircraft and ground support equipment. These linear scaling factors were based on currently published studies comparing standard diesel and jet fuels with alternative jet fuels. It was found that alternative jet fuels lower or maintain all air pollutant emissions considered (primary particulate matter, sulfur oxides, nitrous oxides, unburned hydrocarbons and carbon monoxide) for both aircraft and ground support equipment.

To quantify the potential benefits of changing fuel composition on ambient particulate matter concentrations, a study of the Atlanta Hartsfield Jackson International Airport was completed using both emissions inventory analysis and atmospheric modeling. The atmospheric modeling captures both primary particulate matter and other emissions that react in the atmosphere to form secondary particulate matter. It was found that the use of an ultra low sulfur jet fuel in aircraft gas turbines could reduce the primary particulate matter inventory by 37% and synthetic paraffinic kerosene could reduce the primary particulate matter inventory by 64%. The atmospheric modeling predicts that an ultra low sulfur jet fuel in aircraft could reduce ambient particulate matter concentrations due to aircraft by up to 57% and synthetic paraffinic kerosene could reduce particulate matter concentrations due to aircraft by up to 67%. Thus, this study indicates that the majority of air quality benefits at Atlanta Hartsfield Jackson International Airport that could be derived from the two fuels considered can be captured by removing the sulfur from jet fuel through the use of an ultra low sulfur jet fuel.

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Chapter 1: Introduction

Since 2006, there have been several well publicized commercial test flights using alternative jet fuels. The rise in interest in alternative jet fuels, for both commercial and military use, is a result of the high price, price volatility, lack of fuel source diversity, global climate impacts of aviation and potential air quality benefits of alternative jet fuels. In this thesis, two alternative formulations of jet fuel were examined for their ability to reduce air quality impacts.

When aircraft combust jet fuel, small particles are emitted and additional particles form in the plume. When inhaled, these particles are small enough to travel deep into the lungs and blood stream (Rojo 2007). On a monetary basis, the largest air quality impact of aviation is premature mortality due to ambient particulate matter (Ratliff, Sequeira et al. 2009). The two alternative fuel formulations, Synthetic Paraffinic Kerosene (SPK) and Ultra-Low Sulfur Jet (ULSJ), examined in this thesis reduce air quality impacts by lowering the total amount of emissions that contribute to ambient particulate matter. This reduction is largely a result of the lower sulfur content in both fuels and a reduction in aromatic compounds within the SPK fuel, as compared to standard commercial and military jet fuels.

Aircraft are not, of course, the only source of emissions at an airport. Generators, passenger traffic, and other vehicles all contribute to ambient particulate matter concentrations; however, different entities control the fuel sources. Conversely, ground support equipment, the vehicles on the aircraft side of the airport, tend to draw from a single fuel source. Depending on the airport, ground support equipment may also be operated by the airlines that are also responsible for fueling aircraft. This creates an opportunity for the airlines at an airport to use a single fuel for both the ground support equipment and aircraft as diesel engines are compatible with jet fuel. Using an alternative jet fuel formulation in equipment on the tarmac and in jet aircraft could increase the air quality benefits of the fuel change and may lower airport costs by only requiring one fueling infrastructure.

The impacts of alternative jet fuel use on the air quality surrounding an airport are demonstrated in this thesis through the creation of an emissions inventory analysis using emission scaling factors that are derived herein and with an atmospheric chemistry model. While the scaling factors are generalized and applicable with any airport inventory, the inventory analysis and atmospheric modeling were completed for one sample airport, the Atlanta Hartsfield-Jackson International Airport. Describing the air quality impact of the alternative jet fuel formulation requires both the emissions inventory analysis and the atmospheric chemistry model. The emissions inventory analysis represents what is currently done for environmental impact analyses at airports - focusing primarily on the soot that is directly emitted and some fraction of the readily condensed volatile species. However, it does not capture the secondary particulate matter that forms as a result of reactions with the ambient atmosphere. The atmospheric chemistry model, on the other hand, captures both the primary and secondary contributions to ambient particulate matter.

This thesis begins by discussing aircraft pollution and vehicle compatibility with alternative jet fuels and then presents an air quality analysis of the alternative jet fuel formulations. In Chapter 2, pollutants from air transportation, with an emphasis on those that contribute to ambient particulate matter, are discussed. Chapter 3 examines the viability of alternative jet fuels from a compatibility standpoint. Chapter 4 discusses how ground support emissions are modeled at an airport and proposes a methodology to scale those emissions for alternative jet fuel use. Likewise, Chapter 5 presents a review of changes in aircraft emissions using the alternative jet fuel formulations and proposes a methodology to scale jet aircraft emissions. Chapter 6 describes the methodology to demonstrate changes in emission inventories and ambient particulate matter concentrations using Hartsfield-Jackson International Airport as an example to demonstrate the effects of using an alternative jet fuel on air quality. Chapter 7 discusses the results of the Hartsfield-Jackson simulation. Finally, Chapters 8 and 9 present conclusions and future work.

Chapter 2: Pollutants from Air Transportation

The creation and combustion of hydrocarbon fuels produces a variety of air pollutants. These pollutants include criteria pollutants, greenhouse gases and hazardous air pollutants that harm the environment and human health. The Environmental Protection Agency defines six pollutants (ozone, carbon monoxide, nitrogen dioxide, sulfur dioxide, particulate matter and lead) as criteria pollutants. These pollutants are regulated under the Clean Air Act using the National Ambient Air Quality Standards (NAAQS). Areas of the country that do not meet the NAAQS are referred to as nonattainment areas.

Transportation contributes emissions that lead to elevated levels of all of the criteria pollutants. Aviation contributes to ambient levels of all of these pollutants; however, lead will not be discussed as leaded fuel is primarily used by small piston-driven airplanes, which are not considered in this study, and is no longer in ground transportation fuels.

Although aircraft emissions contribute to ozone, poor visibility and acid rain, the most significant outcome is the impact on human health. On a global basis, ambient ozone caused 21,000 premature mortalities in 2000, and ambient particulate matter was responsible for 348,000 premature mortalities (Watkiss, Pye et al. 2005). A study done in partial response to part of the Energy Policy Act of 2005, calculated 160 premature mortalities (90% confidence interval from 64 to 270 incidences) caused by aircraft air pollution in the United States (Ratliff 2007; Sequeira 2008). As can be seen in Figure 1, 97% of the monetized air quality impact from aircraft emissions is due to premature mortality. Because of its large impact on human health, ambient particulate matter is the focus of this thesis.

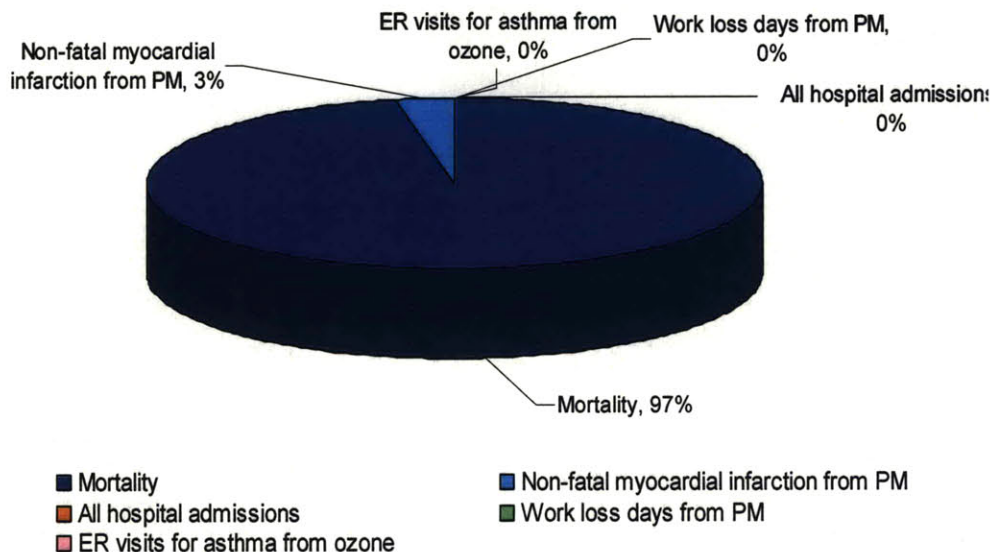


Figure 1 Breakdown of Annual Monetized Health Costs (Sequeira 2008)

Ambient particulate matter is a mix of solid particles and liquid droplets suspended in the air and that is classified by its size. PM_{10} refers to particulate matter with a diameter of 10 μm or less; $PM_{2.5}$ refers to particulate matter with a diameter of 2.5 μm or less. The EPA

designates particles between 10 μm and 2.5 μm as “coarse inhalable particles,” and $\text{PM}_{2.5}$ is designated as “fine particles.” The smaller the particulate matter size, the greater the health impacts (Environmental Protection Agency 2009). Airport GSE produce both PM_{10} and $\text{PM}_{2.5}$, while aircraft produce $\text{PM}_{2.5}$ almost exclusively. An illustration of the scale of particulate matter is shown below in Figure 2.

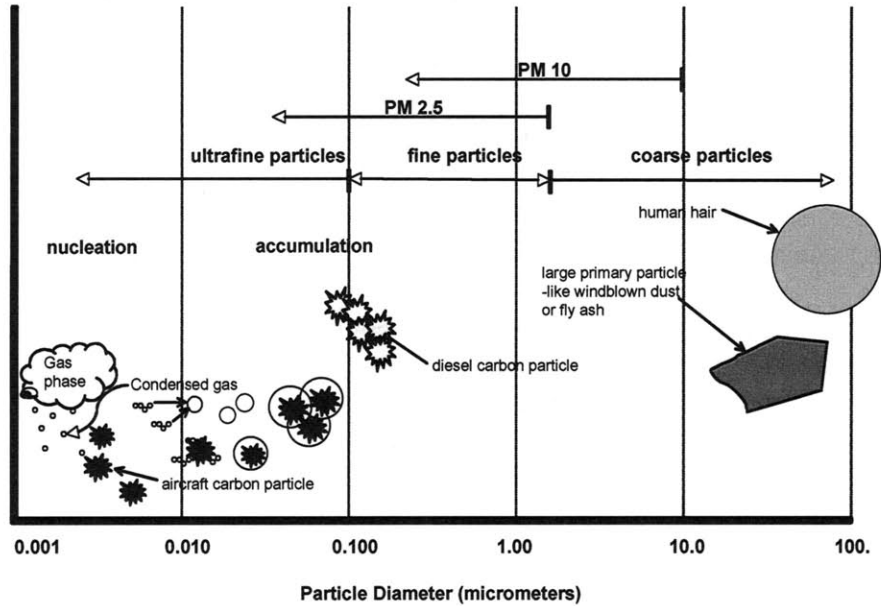


Figure 2 Illustration of Particulate Matter Size (Whitefield et al. 2008)

In addition to being classified according to size, emissions that contribute to ambient particulate matter can also be classified according to where is formed. This subdivision, which is illustrated in Figure 3, creates two additional categories, primary and secondary particulate matter. Aircraft primary particulate matter is formed within the engine and can be measured in the engine exhaust. This includes nonvolatile, solid particles that are formed during combustion (soot, elemental carbon, or black carbon) and liquid particles that form near the combustor exit from volatile components. The volatile component is created from unburned organic compounds, sulfuric acid, and lube oil (Ratliff 2007). Secondary particulate matter forms from gaseous precursor emissions, mainly NO_x and SO_x , that react with compounds, (e.g., ammonia), in the ambient environment. Diesel engines also produce primary particulate matter and gaseous secondary particulate matter precursor emissions of NO_x and SO_x .

The far left column of Figure 3 shows, in a somewhat rudimentary manner, the components of jet fuel composition that lead to emissions that contribute to ambient pollution that affects human health. Reducing the fuel sulfur content and aromatic compound contents of the jet fuel are the most straightforward ways to reduce aviation’s contribution to ambient particulate matter. As shown in Table 1, which presents the apportionment of various $\text{PM}_{2.5}$ species to premature mortality, 14% of annual mortalities are estimated to result from primary, nonvolatile particulate matter. 12% to 50% of annual mortalities are estimated to result from fuel sulfur content in the form of primary particulate matter and secondary particulate matter that is formed from ammonium

sulfate. It should be noted that Brunelle-Yeung's (2009) estimate of health impacts does not include particle bound water while Sequeira's (2008) does include particle bound water.

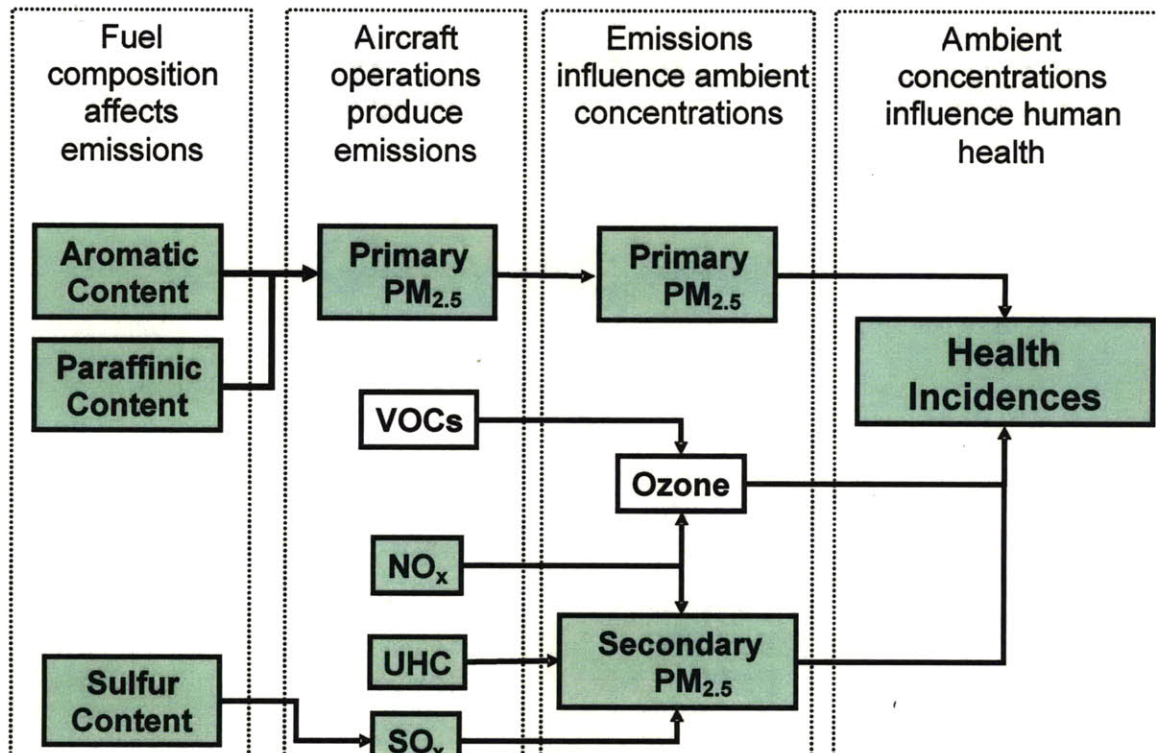


Figure 3 Emission Pathways to Health Impacts. Modified from Sequeira (2008)

Table 1 Yearly Estimates of Premature Mortality by Component of Ambient PM_{2.5}

	Primary PM _{2.5} Nonvolatile	Primary PM _{2.5} Organics	Primary PM _{2.5} Sulfur	Secondary PM _{2.5} Ammonium Sulfate	Secondary PM _{2.5} Ammonium Nitrate
Energy Policy Act Inventory (Sequeira 2008)	14%	18%	4%	46%	18%
RSM v2 (Brunelle-Yeung 2009)	14%	4%	12%*	*	70%

*Brunelle-Yeung (2009) estimates do not separate primary and secondary particulate matter from sulfur emissions and health impact calculations do not include particle bound water.

The question of reducing emissions that contribute to ambient particulate matter is especially salient to airport operators located in nonattainment areas. As shown in Figure 4, many of the nation's largest airports, including Los Angeles International Airport, the Hartsfield-Jackson Atlanta International Airport, Chicago O'Hare International Airport and Washington Dulles International Airport are located within PM_{2.5} nonattainment areas as designated by the EPA.



Partial Counties are shown as whole counties

Figure 4 EPA PM_{2.5} Nonattainment Areas (Environmental Protection Agency 2008)

Chapter 3: Alternative Fuels Considered

Over the years, many alternative means of fueling aircraft have been considered. These range from liquid hydrogen, liquid fuels derived from coal, fuels from algae oil, and solar power among others (Sloop 1978; Fildes 2007; Pae 2009). This thesis, however, focuses on drop-in alternative jet fuels that are viable with the current fleet of commercial passenger aircraft. A drop-in alternative fuel is one that does not require fundamental modification or redesign of today's aircraft; thus, an aircraft burning traditional petroleum-derived jet fuel would also be able to burn the alternative fuels discussed here.

Traditional jet fuel is a product of refined crude oil like gasoline or diesel fuel. To be considered a drop-in fuel, the alternative fuel must be comprised of hydrocarbons and have properties that are similar to traditional jet fuel. The major characteristics to be considered are the energy content, freeze point, vapor pressure, flash point, thermal stability, and lubricity. Acceptable values for these properties are set by two standards in the United States. Commercial users burn Jet A which is standardized under ASTM D 1655; military users predominantly burn JP-8. The major differences between the fuel specifications are the mandatory antioxidant, corrosion, icing inhibitor and static dissipater additives in JP-8 that are not typically used in Jet A (Chevron 2006).

The characteristic of an alternative jet fuel that determines aircraft performance is the energy content. The energy content can be measured either volumetrically, referred to as the energy density, or gravimetrically, referred to as the specific energy. An ideal aircraft fuel has both high energy density and a high specific energy; this means the fuel both takes up comparatively less space and requires the aircraft to haul comparatively less fuel weight. If the energy density is not sufficient, there may not be enough room in the aircraft's fuel tanks to carry enough fuel to reach the desired destination. If the specific energy is not sufficient, the aircraft will have to carry more fuel, making the aircraft heavier and again requiring extra fuel.

Hileman et al. (2010) surveyed a broad variety of fuels and the resulting distribution of fuel heats of combustion can be seen below in Figure 5. The liquid fuels shown in Figure 5 span a wide range of energy densities and specific energies. Jet A is the most attractive fuel from an energy density perspective. Biodiesel is not considered a drop-in fuel due to its reduced energy content, relatively high freezing point and poor thermal stability. The alcohols, butanol and ethanol, are also not viable drop-in fuels due to low energy content and incompatible flash points and vapor pressures. The fuels that are identified as drop-in fuels can be seen near Jet A in Figure 5; they are Synthetic Paraffinic Kerosene (SPK) and Ultra Low Sulfur Jet fuel (ULSJ) (Hileman et al. 2010). In the following sections, basic information on these fuels, their compatibility with current aircraft and their compatibility with diesel engines will be discussed.

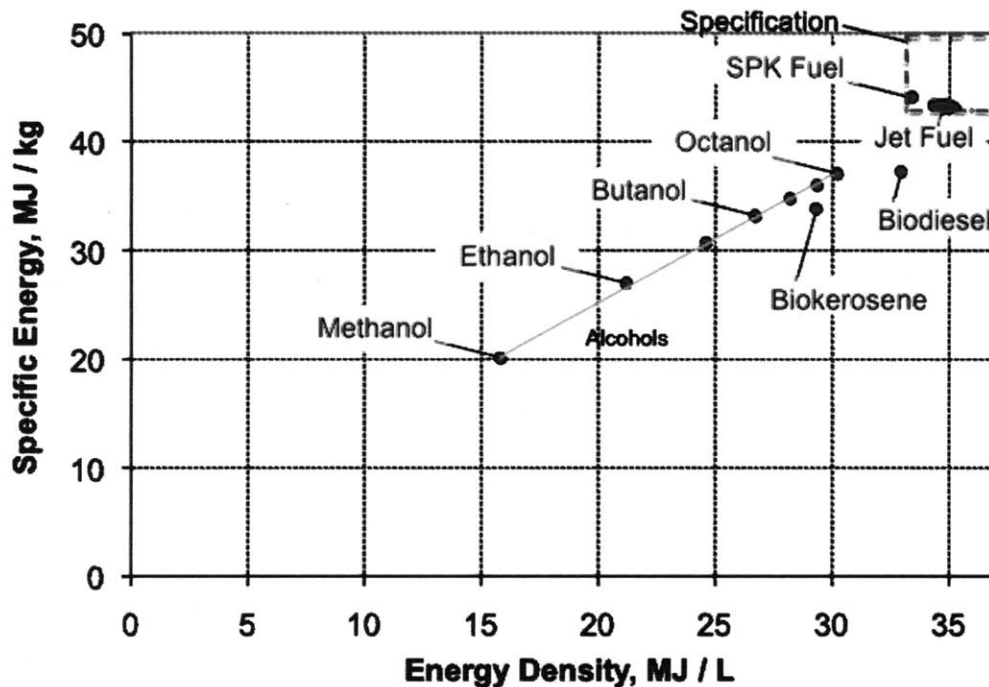


Figure 5 Heat of Combustion for Alternative Jet Fuels (Hileman et al. 2010)
 The box labeled specification corresponds to the density range specified in ASTM D1655.

3.1 Synthetic Paraffinic Kerosene

Synthetic paraffinic kerosene (SPK), as the name implies, is created from sources other than conventional petroleum, is similar to kerosene and is composed of alkanes (non-aromatic hydrocarbon chains). SPK fuels are inherently low to zero sulfur fuels and because of their chemical composition have high specific energy. Pure SPK fuels do not contain aromatic compounds though synthetic aromatics may be added. SPK fuels include Fischer-Tropsch derived fuels as well as hydroprocessed renewable oils. Renewable oils are biologically derived oils from sources such as soybeans, algae and tallow. In the aviation context, hydroprocessed renewable oils are referred to as hydroprocessed renewable jet (HRJ). The differences between Fischer-Tropsch fuels and hydroprocessed renewable oils are the processing and the feedstocks; the end fuels are nearly identical. F-T and HRJ fuels are currently being considered for jet fuel certification with a 50/50 F-T Jet A blend having been approved by ASTM (Commercial Aviation Alternative Fuels Initiative 2009).

3.1.1 Fischer-Tropsch Jet Fuel

Fischer-Tropsch synthesis was initially created by Franz Fischer and Hans Tropsch in the 1920s. Nazi Germany and Japan both created synthetic fuels during World War II using this process. South Africa also started using F-T synthesis to create fuels during apartheid when it was unable to import petroleum, and it continues to use the process today (Alleman and McCormick 2003). There is a renewed interest in Fischer-Tropsch fuels for their ability to enhance supply security and for their potential reduction in greenhouse gas emissions.

Feedstocks ranging from biomass to natural gas to coal can be used with the Fischer-Tropsch process. These fuels are often referred to by their originating feedstock, such as biomass to liquid (BTL), natural gas to liquid (GTL), coal to liquid (CTL), and co-fired coal and biomass to liquid (CBTL). Feedstocks are first gasified to create the syngas (a mixture of carbon monoxide and hydrogen). The syngas is then processed with a catalyst to create a range of hydrocarbons from methane to wax. Because the catalysts are sensitive to sulfur, the syngas is cleansed of sulfur and the resulting fuel has essentially zero sulfur. The hydrocarbons produced at the end of the catalyst step are then upgraded using hydrocracking to create naphtha, diesel fuel, and jet fuel.

3.1.2 Hydroprocessed Renewable Jet Fuel

Hydroprocessed renewable fuels are in the broader category of refined renewable oils. These are biological oils derived from plants or animal fats that are refined into a variety of end fuels including hydroprocessed renewable diesel (HRD) and hydroprocessed renewable jet (HRJ). Unlike biodiesels, which are generally composed of fatty acid methyl ester groups (FAMES) that contain oxygen, refined renewable oils are strictly hydrocarbons. In the refining processing, the oxygen atoms are removed by reacting the oil with hydrogen. A simplified diagram of the refining process is shown below in Figure 6.

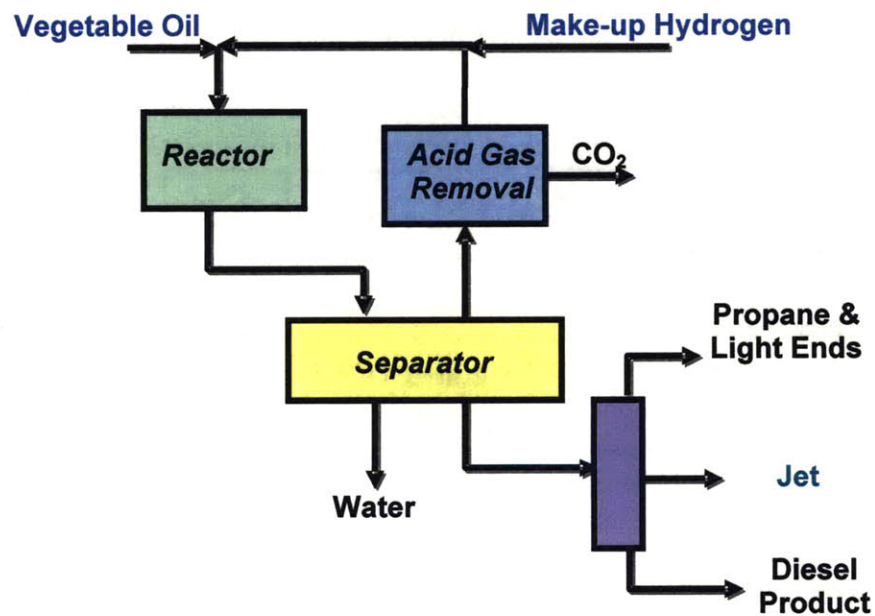


Figure 6 Hydroprocessed oil refining process. Adapted from UOP Ecofinery (Marker et al. 2007)

Companies developing refined renewable oil processes include UOP Honeywell and Eni, Tyson in partnership with ConocoPhillips, Syntroleum and Neste Oil (Department of Defense 2007; Gross 2007; Tyson Foods Inc 2007). Of these companies, UOP Honeywell and Syntroleum are creating fuels tailored to jet fuel specifications with Department of Defense funding (Department of Defense 2007; Gross 2007).

3.1.3 Experience with SPK Fuels in Diesel Engines

In this thesis, the characterization of SPK in diesel engines is derived mostly from the use of Fischer-Tropsch diesel fuel and HRD, not the SPK fuels considered in this study. The main differences between these two fuels are density, aromatic content and cetane number. Due to their low sulfur and low aromatic content, Fischer-Tropsch diesel fuels have been tested extensively for their air quality benefits (Cheng et al. 1999; Clark et al. 1999; DeWitt et al. 2008; Clark et al. 1999; Kidoguchi et al. 2000; Ng et al. 2008; Nord et al. 2002; Schaberg et al. 1997; Sirman et al. 2000; Tao Wu et al. 2007). These tests tend to be dynamometer-based, short term and focused almost exclusively on emissions. Thus, the published literature on long term engine effects is not as well developed (Alleman and McCormick 2003). There have, however, been Fischer-Tropsch pilot programs in California and Sweden as well as the many years of experience in South Africa. Fischer-Tropsch blends are also currently marketed in Europe and Thailand as premium diesel blends (U.S. Department of Energy Office of Energy Efficiency and Renewable Energy 2007).

3.1.4 Experience with SPK Fuels in Jet Engines

Experience using SPK in jet engines comes from both military and commercial testing. As of 1999, aircraft departing from O.R. Tambo International Airport in Johannesburg, South Africa may receive up to 50% SPK in their fuel tanks. The U.S. Air Force has performed various experiments and test flights for compatibility and emission changes (Kimberly 2006; Lopez 2006; Woodbury 2006; Corporan, DeWitt et al. 2007; Corporan et al. 2007; Gross 2007). There have also been numerous, and well publicized commercial aircraft test flights including those performed by Airbus, Boeing, Japan Airlines and Air New Zealand (Hileman et al. 2009). There has also been emission testing performed on commercial engines such as the Alternative Aviation Fuel Experiment (AAFEX) (Anderson 2009; DeWitt and Corporan 2009).

3.2 Ultra Low Sulfur Jet

Ultra Low Sulfur Jet (ULSJ) fuel is a desulfurized version of traditional petroleum derived jet fuel. An analogy to ULSJ is ultra-low sulfur diesel fuel (ULSD). The desulfurization process that is assumed for the creation of ULSJ, hydrodesulfurization, is already widely used for diesel fuels. The United States, European Union, Japan, Sweden and Australia already mandate low sulfur contents in diesel fuels as can be seen in Table 2. This reduction in sulfur was prompted by public health and environmental concerns; an ultra low sulfur diesel standard allows for particle traps that are poisoned by higher sulfur fuels. For this study, it assumed that the ULSJ sulfur limit will mirror the U.S. ULSD standard at 15ppm. Research is currently being conducted to examine the environmental impacts of using ULSJ on both global climate change and regional and international air quality (Partnership for AiR Transportation Noise and Emissions Reduction 2009).

Table 2 World-Wide Ultra Low Sulfur Diesel Regulation for On-Road Use

	Sulfur Content (ppm)	Compliance Year
United States	15	2006
European Union	50	2003
	10	2009
Australia	50	2003
Sweden	10	1991
Japan	50	2003
	10	2008

3.2.1 Experience with Ultra Low Sulfur Jet Fuel in Diesel Engines

There is no known direct experience with ultra low sulfur jet fuel in diesel engines as the sulfur in jet fuel is not regulated to an ultra low sulfur level. There is, however, much experience with standard jet fuel in diesel engines. Most of this experience derives from the Single Battlefield Fuel Initiative. The experience with jet fuel in diesel engines arises from military use because jet fuel is not commercially allowed in diesel engines due to fuel tax differences. The Single Battlefield Fuel Initiative refers to the U.S. military's decision to simplify logistics with one fuel for all equipment when possible. Through the initiative, there are more than 20 years of experience with jet fuel use in diesel engines. The Single Battlefield Fuel concept began in the late 1970s in response to differing fuel requirements by the U.S. Air Force and Army (ACOM-TARDEC 2001).

The transition to land vehicles operating on JP-8 was first prompted by unusually cold winters in Europe in the 1980s. The cold weather produced cold flow problems, waxing and high viscosity in the diesel fuel. As a result, the military began mixing jet fuel, with its significantly improved cold flow properties, and diesel in a 1:1 ratio. This mix was adopted by NATO as fuel F-65 and standardizing on JP-8 became a NATO initiative. At this time, the U.S. Army already had experience with the use of jet fuel in ground equipment. Due to its cold weather properties, the Army has been operating on jet fuel in Alaska since the early 1970s. This included all diesel equipment and vehicles (ACOM-TARDEC 2001).

Large scale testing of jet fuel in military vehicles was initiated in 1988 at Fort Bliss, Texas. During the testing, over 2,800 vehicles were transitioned from diesel fuel to JP-8. Changes in performance and maintenance were monitored for both tactical and non-tactical vehicles. In addition to monitoring equipment at Fort Bliss, the military conducted 10,000 mile performance tests using jet fuel in diesel engines. At the end of the testing period, no major problems were encountered, and Fort Bliss petitioned to continue using JP-8 as a diesel fuel replacement. More than 19 bases have now converted to JP-8. In 1990, Operation Desert Shield utilized the Single Battlefield Fuel strategy with JP-8. The U.S. military was granted permission by the U.S. Environmental Protection Agency to use JP-8 for domestic on and off-road diesel engine applications in 1995. The *JP-8 Single Fuel Forward, Information Compendium* is periodically updated to include relevant testing and experience. Additionally, France, Norway, the United

Kingdom, and the Netherlands accept standard NATO jet fuel as a diesel fuel substitute (ACOM-TARDEC 2001).

3.2.2 Experience with Ultra Low Sulfur Jet Fuel in Jet Engines

As will be discussed in depth in section 5.2, the maximum sulfur content of commercial jet fuel is 3,000 ppm; however, the majority of jet fuel has lower sulfur content with some samples of military jet fuel and commercial jet fuel containing 15ppm or less. However, the ultimate use of these low sulfur fuels is not tracked.

3.3 Compatibility Concerns with Alternative Jet Fuels

The major issues identified with switching to alternatives to Jet A are the processing required to reach ultra low sulfur contents and the lack of aromatic compounds in SPK fuels. Many of the same issues arise for both diesel engines and aircraft engines. Low aromatic content is linked to decreased seal swelling, and the processing typically used to create low sulfur content fuel can result in low fuel lubricity. These concerns are described more fully in the following sub-sections.

3.3.1 Diesel Engine Compatibility Concerns

The first concern for diesel engines is the low lubricity associated with ULSJ and SPK fuels. F-T diesel fuels, for example, have shown lubricity well below accepted standards for diesel fuel (Alleman and McCormick 2003). In the diesel industry, the low lubricity concerns with ULSD and F-T diesel fuels have been addressed with fuel additives (Harley 2002; Chevron 2007; Mobile undated). The additives contain esters (10-50 ppm) or fatty acids (20-250 ppm, Chevron 2007). Because of concerns with thermal stability in aviation gas turbine use, these additives are not appropriate for use in jet fuel; however, the CI/LI additive used in JP-8 should suffice in improving lubricity for diesel engines.

The necessity of a lubricity enhancer for SPK fuels in diesel engines is yet undecided. Without a lubricity enhancer the military found increased wear on fuel pumps (ACOM-TARDEC 2001). However, in 2006, the California Energy Commission noted that based on its experience there was no reported increased engine maintenance for diesel engines vehicles using F-T diesel fuels. Alleman and McCormick (2003) suggest that long term testing is still required to determine diesel engine compatibility.

The second concern is related to the operation of fuel pumps in very hot conditions. During Desert Shield/Storm, the military ground vehicles were fueled with a low sulfur Jet A-1, and restarting High Mobility Multipurpose Wheeled Vehicles after reaching operating temperature became difficult or impossible with temperatures over 104°F (ACOM-TARDEC 2001). This difficulty occurred in a specific (model 2DB) Stanadyne fuel pump and was traced to low sulfur fuel content, low fuel viscosity and dirt contamination combined with the lack of lubricity additive that is mandated for JP-8. Model 2DB fuel pumps are found, though not exclusively, in GM 6.2 and 6.5 liter engines. In response to the low viscosity fuel and restarting issues, Stanadyne issued four service bulletins (see Appendix A). Bulletin 484R specifically addresses the hot restart issues with a new hydraulic head and rotary assembly; the other service bulletins provide for fuel pump changes intended to specifically adapt to low viscosity fuels, including

changing certain seal components. With the exception of the Stanadyne fuel pump, however, the military has found no required modifications or adjustments to engines (ACOM-TARDEC 2001); though, Fernandes et al. (2007) showed that performance could be improved by specifically tuning diesel engines for jet fuel.

In its experience, the military did not find any increased maintenance requirements in using jet fuel in diesel engines; on the contrary, it found several advantages of using jet fuel in diesel engines. These include reduced nozzle fouling, decreased fuel filter replacement intervals, extended oil change intervals, reduced potential for microbiological growth in fuel tanks and reduced water emulsification problems in fuel tanks (ACOM-TARDEC 2001). With sufficient additives, the military also found reduced wear on components and reduced potential for fuel system corrosion (ACOM-TARDEC 2001).

Based on these two observations, either an ULSJ or an SPK fuel should be appropriate for use in diesel engines provided lubricity issues are addressed with additives and fuel pump operations is monitored.

3.3.2 Jet Engine Compatibility Concerns

The major concerns for using alternative fuels in jet engines are low lubricity and fuel leakage due to reduced elastomeric swelling caused by a fuel with few aromatic compounds. As above, lubricity concerns may be mitigated using a fuel lubricity enhancer such as those already mandated for military jet fuel. If seals do not swell properly, fuel leakage may occur at joints in the fuel system. The standard material for these seals has been Buna-N rubber; however, leakage due to seal swell is unlikely to be an issue with either a ULSJ or SPK fuel blend because ULSJ will not be low in aromatic compounds and although SPK fuel has zero aromatic compounds, the jet fuel community are cognizant of possible elastomeric complications and an 8% minimum aromatic compound content is currently being used as a “rule-of-thumb” for an acceptable safe aromatic compound content in jet fuel (Rumizen 2009). For example, a 50% F-T jet blend has been approved by the United Kingdom Ministry of Defense Turbine Fuel Standard as the mixture is likely to provide a minimum 8% aromatic compound content (2007; Moses et al. 2007; Moses et al. 2003). Elastomers tested with synthetic jet fuel containing 7.2% to 16.9% aromatic compounds had the same response as with traditional Jet A-1 (Moses et al. 2003). If, however, a fuel with significantly lower aromatic compound content is used, such as pure SPK, the Buna-N rubber seals will need to be identified and replaced with fluoroelastomers to prevent fuel leakage. Fluoroelastomers have historically been used within aircraft and a 2008 study demonstrated that fluorosilicone and fluoroelastomers produce adequate seal swell with F-T fuels (DeWitt et al. 2008). Although the cost difference between these seals is small, the maintenance expenses for replacing Buna-N seals could be substantial.

3.4 Changes in Fuel Use

The different fuel properties of SPK or ULSJ could produce a change in fuel use in both diesel engines and aircraft. As discussed below, the fuel burn change in diesel engines

that use alternative jet fuels varies based on the engine type and testing cycle whereas the fuel burn change in aircraft depends on the fuel specific energy.

3.4.1 Changes in Fuel Use in Diesel Engines

Studies comparing the use of a F-T diesel fuel and HRD to conventional diesel fuel in diesel engines show conflicting results. Schaberg et al. (1997) found a 1% to 2.9% decrease in F-T diesel fuel use using a transient engine test with a heavy duty DDC 60 Series engine. However, in full-vehicle dynamometer testing completed with a diesel bus and semi-truck tractor, Clark et al. (1999) found a 4.4% average F-T diesel fuel use increase. Using up to an 85% blend of HRD, Rantanen et al. (2005) found no change in fuel use.

Military studies examining jet fuel use in diesel engines also show conflicting results. Initial predictions ranged from a 1% to 5% increase in fuel usage based on the change in energy density (BTU/gallon) of the fuels (2001) while engine testing indicated a 2% increase in fuel use (2001). Additional testing by Fernandes et al. (2007) initially found an increased fuel consumption of 1% with JP-8 when testing engines at low load but then found a decreased fuel consumption of approximately 1% with modified injection timing (Fernandes et al. 2007). Yost et al. (1992) found varying levels of fuel consumption based on loading which ranged from -5.4% to 3.9% (Yost 1992). Overall, military field testing of diesel engine vehicles burning jet fuel indicates that “there has been no indication of a significant increase in fuel consumption being evidenced (2001).” Due to the variation in fuel use change across studies, both positive and negative, it was assumed herein that there is no change in fuel use when using either SPK or ULSJ within diesel engines.

3.4.2 Changes in Jet Fuel Use in Jet Engines

Aircraft engine combustion of either SPK or ULSJ could result in a change in fuel use as energy content is the driver of fuel consumption. For this study, the change in fuel use is estimated based on the ratio of fuel specific energy. As discussed previously, the energy content of a fuel can be determined on a gravimetric or volumetric basis. If the energy density (volume) is not sufficient, there may not be enough room in the aircraft’s fuel tanks to meet the mission requirements. If the specific energy (gravimetric) is not sufficient, the aircraft will have to carry more fuel, making the aircraft heavier and again requiring extra fuel. Because most commercial aircraft do not fly with full tanks, specific energy is more salient for calculating a change in fuel use.

The specific energy of Jet A, ULSJ and SPK have been estimated by Hileman et al. (2010). The values relative to Jet A are shown below in Table 3. The baseline value of Jet A is based on the average value from the PQIS database of military JP-8 jet fuel. The specific energy for ULSJ is based on the decrease in energy density and related increase in hydrogen content due to the hydrodesulfurization process. SPK specific energy values are based on a literature review of actual fuel testing. Both SPK and ULSJ fuels in aircraft are predicted to lead to a marginal decrease in fuel consumption, as measured on a mass basis.

Table 3 Fuel Scaling factors and Energy Content for Aircraft Fuels

Fuel	Specific Energy (MJ/kg)	Fuel Scaling Factor
Jet A	43.2	1
ULSJ	43.4	0.995
SPK	44.1	0.979

Chapter 4: Ground Support Equipment (GSE) Emissions

The classification of GSE includes all of the vehicles on the tarmac, or aircraft side, of the airport. They are classified as off-road vehicles and as such conform to different regulations than standard, on-road diesel vehicles (Environmental Protection Agency 2004). A full list of GSE modeled in this work is given in Table 44.

Table 4 Full List of GSE Types Modeled

Air Conditioner	Bobtail	Catering Truck	Ground Power Unit	Service Truck
Air Start	Cabin Service Truck	Deicer	Hydrant Truck	Sweeper
Aircraft Tractor	Cargo Loader	Fork Lift	Lavatory Truck	Water Service
Baggage Tractor	Cargo Tractor	Fuel Truck	Lift	
Belt Loader	Cart	Generator	Passenger Stand	

Here, the emissions for GSE were modeled using a modified version of the Emissions Dispersion Modeling System (EDMS). EDMS is the Federal Aviation Administration's mandatory regulatory tool for modeling emissions. EDMS creates an emissions inventory for all of the emission sources at the airport, including aircraft, GSE and auxiliary power units (APUs) (Federal Aviation Administration 2009). The aircraft section of the model will be discussed in the following chapter. APUs were not included in the emissions scaling due to a lack of data. As is elaborated on in 4.1, EDMS uses emissions factors derived from the EPA's NONROAD model for GSE emissions.

4.1 Emissions Modeling for Baseline Fuel

EDMS was used to calculate the GSE emissions for conventional diesel fuel based on the population of GSE, the time each unit is operated and an emissions factor:

$$E_{GSE, f, p} = \sum_{GSE} t \cdot BHP \cdot LF \cdot EF_{GSE, f, p}$$

Equation 1

where

$E_{GSE, f, p}$ is the emissions inventory in grams of pollutant p using fuel f,

t is the time operated (hours),

BHP is the rated brake horsepower of the GSE engine (bhp)

LF is the load factor, discussed below, and

$EF_{GSE, f, p}$ is the emissions factor for pollutant p using fuel f in $\frac{g}{bhp \cdot hr}$.

The load factor, LF, describes what fraction of the total engine capacity is used. An LF of one indicates that the engine is being run at 100% capacity; an LF of 0.5 indicates the engine is being run at 50% capacity. The load factors are constants determined by the EPA (Environmental Protection Agency 2004). The emissions factors are given by the EPA's NONROAD model.

The NONROAD model is based largely on the horsepower of an engine, the fuel use and the time operated; many assumptions have been made about the technology in the engines and homogeneity of emissions characteristics across engines of the same age, horsepower and end-use. The specific emissions factors, which describe the quantity of pollutant produced per horsepower per hour operated, are described for ranges of engine ratings and the emissions regulations or ‘tier’ that they are subject to. An example of these emissions factors is shown below in Table 5.

Table 5 Sample Emission NO_x Emissions Factors in Grams per Brake Horsepower Hour

Brake Horsepower Hour	NO _x Emissions Factor	
	Tier 2	Tier 3
≥ 50 to <100	5.2	3.3
≥ 100 to <175	4.5	2.8
≥ 175 to <300	4.5	2.8

These emissions factors were determined for the different engine ranges based upon data from off-road engine testing and similar on-road engine models. These emissions factors were then adjusted for the age of the engines through deterioration factors and the sulfur content of the fuel, as applicable. The individual equations for pollutants are discussed below in the scaling section for each pollutant.

Emissions factors (EF) and emissions inventories (E) were estimated for each fuel and pollutant for both ground support equipment (GSE) and aircraft (AC) based on the results from EDMS using conventional diesel and jet fuels. The fuel abbreviations and pollutant abbreviations are shown below in Table 6 and Table 7. Note that in Chapter 4, PM refers exclusively to fine primary particulate matter emissions. This includes both nonvolatile and volatile components. In Chapter 5, the components of primary particulate matter are examined individually.

Table 6 Fuel and Equipment Nomenclature

Fuel	Abbreviation	Equipment
Conventional Diesel	Diesel	GSE
Ultra Low Sulfur Diesel	ULSD	GSE
Conventional Jet Fuel	Jet	AC
Ultra Low Sulfur Jet Fuel	ULSJ	AC/GSE
Synthetic Paraffinic Kerosene	SPK	AC/GSE

Table 7 Pollutant Nomenclature for Equations

Pollutant	Abbreviation
Unburned Hydrocarbons	HC
Carbon Monoxide	CO
Nitrogen Oxides	NO _x
Sulfur Oxides	SO _x
Primary Particulate Matter (diameter less than 2.5 μm)	PM

To estimate an emissions inventory, EDMS relies on information about the GSE mix and the amount of time the GSE are being operated. As shown in the decision tree in Figure 7, the time operated, *t*, and GSE mix (year of manufacture and engine horse power) can be set by the user, EDMS or a hybrid of the two. With the user input mode, the user enters the GSE mix and the time operated for each unit. In the hybrid mode, EDMS has two options for determining GSE mix and run time. The first option is that the user inputs the mix of GSE, and the user individually assigns the GSE to an aircraft. The second option is that the user inputs the mix of GSE and EDMS automatically assigns the GSE to an aircraft. The time of use is then determined by the aircraft's activity. In the full EDMS mode, the user only inputs the aircraft flight schedule and EDMS determines both the mix of GSE and assigns them to aircraft. Again, the time of use is then based on the aircraft activity.

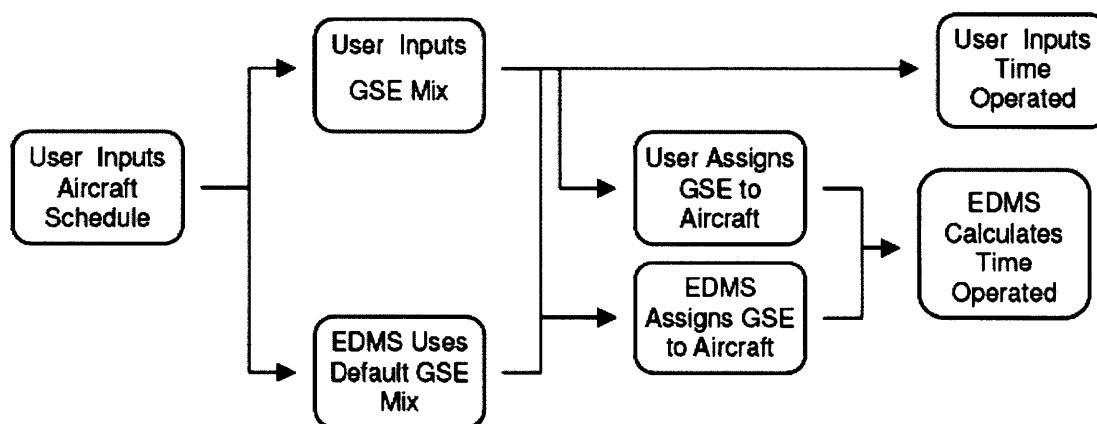


Figure 7 Decision Tree for Setting GSE Mix and Time Operated in EDMS

4.2 Fuel Properties Affecting Diesel Engine Emissions

As will be discussed more in depth in the following sections, the emissions from diesel GSE were scaled based on experimental results comparing diesel emissions to emissions from alternative fuels. The change in emissions depends on a variety of factors, including engine age, type of testing cycle, installed pollution controls and fuel properties such as cetane number, fuel density and aromatic content (Lee et al. 1998). Reducing fuel sulfur content also has the effect of reducing PM emissions, but this is only the case when sulfur levels drop significantly, such as from 3,000 ppm to 500 ppm. At sulfur levels below 500 ppm, the driving factor behind PM emissions becomes PM filters and emission traps (Lee

et al. 1998). The effects of these different fuel properties on NO_x, HC, CO and PM emissions are qualitatively summarized in Table 8. Because the experimental results surveyed to create scaling factors represented a variety of engine and test cycle types, it was not unexpected that variations occurred in the change of pollutant emissions across studies. Averaging across a variety of studies was also appropriate to scaling a GSE fleet composed of a variety of different engine types with different operation cycles.

Table 8 Select Fuel Properties Effect On Diesel Engine Emissions (Lee et al. 1998)
 Entries with 0/↓ indicate that the property affects high emission engines but not low emission engines. Note that PM indicates primary particulate matter emissions.

Fuel Modification	HC	CO	NO _x	PM
Increase Cetane	0/↓	0/↓	↓	0
Reduce Total Aromatics	0	0	↓	0
Reduce Density	↑↑	↑	↓	0/↓

The fuel properties shown in Table 8, cetane number, aromatic compound content and density, change across the alternative fuels considered. These changes in fuel properties are shown in Table 9, Table 10 and Table 11, and are discussed below.

The cetane numbers for diesel, JP-8, synthetic diesel and synthetic jets fuels are shown in Table 9. An average cetane number was not available for SPK fuels, however, two sample cetane numbers from a Syntroleum SPK (S8) and Shell F-T Jet were provided by Tim Edwards at the Wright-Patterson Air Force Base (Edwards 2008). A third Syntroleum sample for S5 was also found in the literature. Syntroleum's S5 fuel was created to meet military specification for JP-5 (Frame et al. 2004). JP-5 is a turbine fuel for the U.S. Navy; it has a higher flash point than commercial jet fuel, which is required to meet more stringent safety standards for aircraft carrier operation. All four synthetic fuel categories (F-T diesel, S5, S8 and Shell F-T jet) showed an increase in cetane of at least 14 points relative to either diesel fuel or JP-8, which were similar. The cetane numbers of diesel and jet fuels (in this case JP-8 is used as a surrogate for Jet A) were within one point. The cetane number of F-T diesel fuel was the highest with an average cetane number of 74.5. Based on Table 8, these increases in cetane number may lead to lower HC, CO and NO_x emissions.

Table 9 Cetane Number for Three F-T Jet Fuels, F-T Diesel Fuel, Jet Fuel and Diesel Fuel

Fuel	Cetane	Source
Diesel Fuel	40 (minimum, United States) 45 average	(Alleman and McCormick 2003)
Jet Fuel (JP-8)	45.9	(Bowden and Westbrook 1989; Yost 1992; Yost et al. 1996; Edwards 2008)
	43.2	(Defense Energy Support Center 2008)
Average F-T Diesel	74.0	Appendix B
S5	69.3	(Frame et al. 2004)
S8	57.9	(Edwards 2008)
Shell F-T Jet	59.1	(Edwards 2008)

In Table 10, the density variation across the alternative and diesel fuels are shown. In this case all four synthetic fuel categories (F-T diesel, S5, S8 and Shell F-T jet) as well as jet fuel showed a decrease in density of at least 0.5 kg/L. All of the synthetic fuels have approximately the same density with SPK having the lowest at 0.76 kg/L. Based on Table 8, these decreases in density may lead to higher HC and CO emissions but lower NO_x and PM emissions.

Table 10 Density of F-T Jet Fuels, F-T Diesel Fuel, Jet Fuel and Diesel Fuel

Fuel	Density (kg/L)	Source
Diesel	0.85	(Alleman and McCormick 2003)
Average F-T Diesel	0.77-0.79	(Alleman and McCormick 2003)
Jet Fuel (JP-8)	0.80	(Hileman et al. 2010)
S5	0.77	(Frame et al. 2004)
Average SPK	0.76	(Hileman et al. 2010)

Finally, in Table 11, the aromatic compound content across the alternative and diesel fuels are shown. All of the synthetic fuels exhibit considerably lower aromatic content (less than 3%) as a result of their creation process. Diesel fuel again exhibits the highest aromatic content though in some regions, such as California, aromatic compound contents are 10-20% lower than average due to increased regulation. Based on Table 8, the decreases in aromatic compound content in the alternative fuels relative to diesel fuel may lead to lower NO_x emissions.

Table 11 Aromatic of F-T Jet Fuels, F-T Diesel Fuel, Jet Fuel and Diesel Fuel

Fuel	Aromatic Content (%)	Source
Diesel	~20-35 35 maximum (United States)	(Chevron 2007)
Average F-T Diesel	0.1-2.7	(Alleman and McCormick 2003)
Jet Fuel (Jet A)	18 (JP-8) 25 maximum (Jet A United States)	(Chevron 2006; Defense Energy Support Center 2008)
S5	0.9	(Frame et al. 2004)
Average SPK Jet	<1	(Hileman et al. 2009)

4.3 Unburned Hydrocarbons, Carbon Monoxide, Nitrogen Oxides

The emission factors for unburned hydrocarbons (HC), carbon monoxide (CO) and nitrogen oxides (NO_x) were computed using the same generalized formula:

$$EF_{GSE-diesel-HC,CO,NO_x} = EF_{ss} \cdot TAF \cdot DF$$

Equation 2

where

EF_{ss} is the steady-state experimental or extrapolated emissions factor for each pollutant,

TAF is the Transient Adjustment Factor to correct for non-steady-state operation and

DF is the Deterioration Factor to correct for engine deterioration over time.

Therefore, as shown in Equation 1, the total emissions for a piece of GSE were estimated as the final emissions factor (EF_{HC}, EF_{CO} or EF_{NO_x}) multiplied by the horsepower of the engine and the time operated. It was assumed that the DF and TAF were unaffected by the fuel compositions considered here.

In order to calculate the emissions from use of SPK or ULSJ in GSE, the emission factors were scaled based on experimental data from the literature. The scaling factors were used to directly scale the emissions factors:

$$EF_{GSE-alt-p} = EF_{GSE-diesel-p} \cdot k_p$$

Equation 3

where

EF_{GSE-alt-p} is the emissions factor for pollutant p (HC, NO_x or CO) using SPK or ULSJ fuel,

EF_{GSE-diesel-p} is the emissions factor for pollutant p on diesel fuel and

k_p is the scaling factor for a specific fuel and pollutant.

The change in fuel use is reflected within Equation 3 because the test methodologies, which run for a set distance or time, implicitly include changes in fuel burn. The scaling factors for HC, CO and NO_x emissions are linear with emission factors and the terms in Equation 1 were assumed to be unchanged with fuel composition; therefore, the total GSE emissions inventory rather than individual emissions factors can be examined:

$$E_{GSE-alt-p} = E_{GSE-diesel-p} \cdot k_p$$

Equation 4

This eliminated the need to scale the emissions from individual pieces of GSE.

4.3.1 ULSJ Scaling Factors

Scaling factors for ULSJ were derived from the literature following the same form as Equation 4. The available of testing data for jet fuel in diesel engines was limited. The jet fuel tests performed focused on military needs relating to the Single Battlefield Fuel Initiative; as a result, the testing focused exclusively on heavy duty engines (Yost et al. 1996; Fernandes et al. 2007; Yost 1992), and the jet fuel in the emissions studies considered were military standard, JP-8. The test cycles included both transient and steady-state protocols.

The scaling factors derived from these test are shown in Table 12. As seen in Table 12, CO represented the largest change in emissions with a 34% reduction. There was also an average 10% reduction in HC emissions, and an average 16% reduction in NO_x emissions.

Table 12 GSE ULSJ HC, CO and NO_x Scaling Factors

Pollutant	HC (<i>n</i> =6)	NO _x (<i>n</i> =9)	CO (<i>n</i> =6)
Scaling Factor	0.90	0.84	0.66
Standard Deviation	0.18	0.17	0.11

4.3.2 SPK Scaling Factors

An SPK scaling factor for Equation 4 was developed using experimental testing results comparing F-T diesel to standard diesel fuel. F-T diesel fuels are not substitutes for jet fuel; however, there is only one published diesel engine test of an SPK fuel that the author was aware, but there have been many tests of synthetic paraffinic diesel fuels (e.g., F-T diesel and HRD (Frame et al. 2004)).

One possible difference in the fuel properties between F-T fuels for jet engines and F-T fuels for diesel engines is the cetane number, which reflects the ignition properties of the fuel. Depending on the specific engine properties, an increased cetane number may lower HC, CO, NO_x and PM emissions (Lee et al. 1998). As can be seen in Table 9, the cetane numbers for two potential F-T jet fuels, S8 and a sample of F-T jet fuel from Shell, were lower than the average F-T diesel fuel. The S5 jet fuel, on the other hand, has a cetane

number that was closer to the F-T diesel fuel. Based on these limited data, it was unclear if the F-T jet cetane numbers were inherently lower than the F-T diesel cetane numbers. All of the synthetic fuel cetane numbers reported, however, were significantly higher than that of the average diesel fuel.

Due to the limited data from SPK fuel use in diesel engines (from either F-T jet or HRJ) and their overall similarity to F-T diesel fuels, it was assumed that the emission scaling factors for SPK and F-T diesel fuels were similar. With this assumption, scaling values were derived from F-T diesel fuel tests that compared a certification diesel with an F-T diesel in the same engine using identical test schemes (Schaberg et al. 1997; Schaberg et al. 2000; Fanick et al. 2001; Nord and Haupt 2002; Alleman and McCormick ; Frame 2004; Frame et al. 2004; Rantanen et al. 2005). The certification diesel was a 300ppm Number 2 diesel, and the test schemes used included steady-state testing at multiple load values, United States regulatory transient test cycles (Federal Test Procedure (FTP) and Highway Fuel Economy Test (HFET)) and European test cycles. The vehicles represented in these tests range from a 1.9L Volkswagen Golf to a military 6.2L Hummer. A summary of these results is presented in Table 13.

Table 13 GSE SPK (F-T Diesel Proxy) HC, CO and NO_x Scaling Factors

Pollutant	HC (<i>n</i> =14)	NO _x (<i>n</i> =14)	CO (<i>n</i> =13)
Scaling Factor	0.55	0.87	0.61
Standard Deviation	0.17	0.11	0.15
S5 Test (<i>n</i> =2)	0.33	0.86	0.47

The NO_x scaling factors for the S5 and F-T diesel tests were similar; however, variation was seen both in the CO and HC scaling factors. The S-5 values for HC and CO both fell beyond the standard deviation for the full data set (in which they were included). SPK fuels may further reduce HC and CO emissions, relative to synthetic diesel fuel use, but the lack of data made it difficult to determine. Further testing is needed.

4.4 Sulfur Dioxide

In the NONROAD model, the sulfur dioxide emission factor is based on the sulfur content of the fuel, the unburned hydrocarbon emissions and the quantity of fuel burned. The total sulfur dioxide emissions are equal to the total grams of sulfur combusted minus the amount of sulfur that is bound in unburned hydrocarbons and the amount of sulfur that is bound in PM (primary particulate matter) emissions:

$$EF_{GSE-Alt-SOx} = \delta_{alt} \cdot (BSFC \cdot 453.6 \cdot (1 - soxcnv) - EF_{GSE-alt-HC}) \cdot 0.01 \cdot soxdsI \cdot 2$$

Equation 5

where

$EF_{GSE-alt-SOx}$ is the sulfur oxides emission factor for SPK or ULSJ,

δ_{alt} is the change in brake specific fuel consumption,

$BSFC$ is the Brake Specific Fuel Consumption in $\frac{lbs}{bhp \cdot hr}$,

453.6 is the conversion from pounds to grams,

$soxcnv$ is the fraction of sulfur converted to PM,

$EF_{GSE-alt-HC}$ is the fuel specific unburned hydrocarbon emission factor,

0.01 is the conversion of weight percent to weight fraction,

$soxdsI$ is the sulfur content of the alternative fuel in weight percent and

2 is the grams of SO_2 formed from a gram of sulfur.

The term in parenthesis in Equation 5 reflects the amount of sulfur in the fuel that is left after the sulfur bound in primary particulate matter, reflected in the $(1-soxcnv)$ term, and sulfur bound in unburned hydrocarbons is subtracted. This remaining sulfur is assumed by the model to be bound in SO_2 particles.

For both ULSJ and SPK fuels, the fuel sulfur level, $soxdsI$, was assumed to be 15 ppm (0.15 weight percent). As discussed in 3.2 the ULSJ was assumed at 15 ppm to mirror the United States ULSD standard, and SPK was also assumed to have a sulfur content of 15 ppm due to contamination in pipelines. In reality, the actual sulfur content of these fuels would be less than 15 ppm. For example, the EPA published estimates of sulfur content for NONROAD diesel fuels as seen in Table 14. Note that in 2015, the EPA assumes the fuel sulfur content will be 11 ppm.

Table 14 EPA Estimated Sulfur Content of NONROAD Diesel Fuel (Environmental Protection Agency 2004)

Year	Diesel Fuel Sulfur Content in Weight Percent (48 states)
2005	0.2283
2006	0.2249
2007	0.1140
2008	0.0348
2009	0.0348
2010	0.0163
2011	0.0031
2012	0.0031
2013	0.0031
2014	0.0019
2015	0.0011

4.5 Primary Particulate Matter

The NONROAD model calculates two sizes of primary particulate matter, PM_{2.5} and PM₁₀. The subscript, 2.5 or 10, indicates the maximum diameter in micrometers of the primary particulate matter. The NONROAD model calculates PM₁₀ and assumes that 90% of PM₁₀ is PM_{2.5}. Within Chapter 4, PM refers to primary particulate matter with a diameter less than 2.5 μm and the 90% scaling is implicitly assumed in the calculations.

The NONROAD model calculates PM emission factors based on the vehicle technology type, the sulfur conversion rate and the fuel sulfur content:

$$EF_{GSE-alt-PM} = (EF_{GSE-diesel-PM} - S_{adj}) \cdot k_p$$

Equation 6

where

$EF_{GSE-Alt-PM}$ is the primary particulate matter emission factor for SPK or ULSJ,
 $EF_{GSE-diesel-PM}$ is the primary particulate matter emission factor for the baseline diesel fuel and
 S_{adj} represents the correction term for the sulfur content of the fuel.

S_{adj} is a function of both the sulfur conversion factor, $soxcnv$, and the sulfur content of the fuel:

$$S_{adj} = BSFC \cdot 453.6 \cdot 7 \cdot soxcnv \cdot 0.01 \cdot (soxbas - soxdsl)$$

Equation 7

where

7 is the grams hydrated sulfate per gram sulfur ($H_2SO_4 + 7H_2O$),
0.01 is a conversion from weight percent to weight fraction and
 $soxbas$ is the base fuel's sulfur content in weight percent.

In the NONROAD model, $soxbas$ often refers to the diesel certification fuel value of 3,000 ppm; however, for this model, $soxbas$ refers to the sulfur content of the diesel fuel, either ULSD or that shown in Table 14. The $soxbas-soxdsl$ term therefore represents the difference in sulfur content between the baseline emissions and the fuel being considered.

4.5.1 ULSJ Scaling Factor

The literature review that was conducted for this work did not reveal any diesel PM measurements that directly compare ULSJ with either diesel fuel or ULSD. There are studies comparing diesel fuel and JP-8 that are described in Table 15 (Yost et al. 1996; Fernandes et al. 2007; Yost 1992).

Table 15 Literature Values for Jet Fuel and Diesel Fuel Comparisons
PM denotes primary particulate matter having a diameter less than 2.5 μm .

Study	Jet Sulfur Content (ppm)	Diesel Sulfur Content (ppm)	Engine Type	PM Reduction (%)	Test Type
Fernandes	40	300	DDC 60 Series	67	50% /1800 (3 Set Speeds/Loads)
Fernandes	40	300	DDC 60 Series	23	20%/1200 (3 Set Speeds/Loads)
Fernandes	40	300	DDC 60 Series	55	50% /1200 (3 Set Speeds/Loads)
Yost 1996	700	9,500	DDC 60 Series	22	Transient (Hot)
Yost 1996	700	9,500	GM 6.2L	21	Transient (Hot)
Yost 1992	1,100	350	Isuzu C-40	44	13 Stage Composite
Yost 1992	1,100	350	Deutz F3L912W	66	13 Stage Composite
Yost 1992	1,100	350	Deutz F4L912W	56	13 Stage Composite
Yost 1992	1,100	350	Perkins 4.154	50	13 Stage Composite

As seen in Table 15, there are a variety of fuel sulfur contents in both jet and diesel fuel ranging from 40 ppm to 9,500 ppm. Across all of these studies and fuel sulfur contents, a reduction is seen by using jet fuel instead of diesel fuel. These reductions in PM align with predictions from Table 8 based on fuel composition as the density of jet fuel is less than diesel fuel.

Averaging the above results yielded a scaling factor of 0.48 with a standard deviation of 0.15. The 1996 Yost results were excluded from the scaling factor calculation due to the high fuel sulfur content (9,500 ppm) and its noted effect on PM. Lee et al. (1998) showed that reductions of sulfur content from 3,000 ppm to 500 ppm produced reductions in PM and the 9,500 ppm from Yost (1996) is well in excess of 3,000 ppm.

4.5.2 SPK Scaling Factor

As was done for the HC, CO, and NO_x emissions scaling, F-T diesel fuel was examined as a PM testing proxy for SPK. Sixteen different engine tests were considered to determine scaling factor for PM that would be used as a surrogate for SPK (Schaberg et al. 1997; Cheng and Dibble 1999; Clark et al. 1999; Schaberg et al. 2000; Sirman et al. 2000; Fanick et al. 2001; Nord and Haupt 2002; Alleman and McCormick 2003; Frame et al. 2004; Frame et al. 2004; Rantanen et al. 2005; Tao Wu et al. 2007). These studies

included six light duty engine tests and ten heavy-duty engine tests and included transient test cycles, both hot and cold, and steady state test studies. These studies used a diesel fuel that had baseline fuel sulfur content of 300 ppm; the result was a scaling factor of 0.67 with a standard deviation of 0.067. However, this scaling factor is 0.19 higher than the scaling factor for jet fuel that was derived in Section 4.5.1. The 0.67 scaling factor is also 0.19-0.22 higher than a scaling factor derived from S5. These results are described below in Table 16. The scaling factors for JP-8 and S5 also do not fall within two standard deviations of the F-T diesel scaling factor.

Table 16 PM Scaling Results for JP-8, F-T Diesel and S5 Relative to Diesel
 PM denotes primary particulate matter having a diameter less than 2.5 μm .

Fuel	JP- 8	F-T Diesel	S5
PM Scaling Factor	0.48	0.67	0.47
	$n=7$	$n=16$	$n=2$
	$\sigma=0.15$	$\sigma=0.067$	

Due to the disparity between the jet fuel results (JP-8 and S5) and F-T diesel fuel emissions, the similarity in density between S-5 and JP8, and Lee et al.'s finding that density is a strong driver of PM emissions, it was assumed that the SPK emissions would mirror the scaling factor for the jet fuels with a value of 0.48.

4.6 Comparison of Scaling Factors

The expected changes based on the fuel composition changes discussed in 4.2 are shown in Table 17. The actual changes, in percent reduction, are shown in Table 18.

Table 17 Anticipated Changes in Emissions Based on Fuel Composition Relative to Diesel
 PM denotes primary particulate matter having a diameter less than 2.5 μm .

Fuel Property Change	ULSJ				FT-Diesel (SPK Proxy)			
	HC	NO _x	CO	PM	HC	NO _x	CO	PM
Cetane Number	-	-	-	-	↓	↓	↓	-
Aromatic Content	-	↓	-	-	-	↓	-	-
Density	↑	↓	↑	↓	↑	↓	↑	↓

Table 18 Reductions in Emissions for GSE Relative to Diesel
 PM denotes primary particulate matter having a diameter less than 2.5 μm .

	HC	NO _x	CO	PM
ULSJ	10%	16%	34%	52%
F-T Diesel (SPK Proxy)	45%	13%	39%	33%
S5	67%	14%	53%	53%

As expected, NO_x production from diesel engines operating on SPK, ULSJ and S5 fuels were reduced as compared to diesel fuel. This was expected due to changes in cetane number, aromatic content and density. All three fuels produced reductions within 2% of each other. The reductions for SPK (using F-T diesel fuel as a proxy) and S5 were within

1% indicating that F-T diesel fuel is an appropriate substitute for F-T jet fuel for NO_x scaling.

The trends for HC emissions matched expectations, although the gross reductions did not. Due to the decreased density of jet fuel compared to diesel fuel and the similar cetane number for both fuels, it was expected that HC emissions would increase. The testing, however, reflects a 10% decrease in HC emissions. The expected change for the SPK (using F-T diesel fuel as a proxy) HC emissions was neutral as the decrease in emissions due to cetane number were expected to be offset by an increase in emissions due to a decrease in density. The experimental results, however, reflected a 45%-67% decrease. This may be because cetane has the dominant influence on emissions; it may also be due to the fact that Lee et al. (1998) only explored increasing rather than decreasing density values or it could be due to other uncaptured variables, such as a reduction due to polyaromatic compounds or changes resulting from engine geometry. Some percentage of emissions reduction may also be due to decreased fuel use as discussed in 3.4.1. Additionally, for HC emissions, F-T diesel fuel may be a conservative proxy for SPK jet fuel as the S5 results were 22% lower than the F-T diesel results.

CO emissions were also reduced more than expected. Again, based on Table 17, it was expected that CO emissions would increase with the use of jet fuel and decrease or remain stable for a synthetic fuel; however, all three fuels showed considerable (34-53%) reductions in emissions. As with HC emission changes, this indicates that some element of fuel composition or effect of engine design was not captured. The emission changes also indicate that F-T diesel fuel may be a conservative surrogate for SPK CO emissions as S5 emissions were 14% lower than F-T diesel fuel.

As with both CO and HC emissions, PM emissions reductions matched the expected trend but with greater reductions than expected. Reductions for both ULSJ and SPK were expected due to a decrease in fuel density; however F-T diesel fuel showed similar reductions to S5 and JP8. This again indicates that Lee et al. (1998) did not capture some necessary element of fuel composition or engine design.

Further testing is needed to resolve these issues.

Chapter 5: Jet Aircraft Emissions

In addition to GSE, EDMS also calculates emissions from jet aircraft. The user inputs a flight schedule, which includes the types of aircraft being operated and how many operations each aircraft undertakes. The emissions are then calculated based on the engine type, the number of operations and the thrust and fuel burn of the aircraft over the landing and take-off cycle. Unlike GSE scaling factors that are based on multiple tests and diesel surrogates, the aviation scaling factors are based on fewer tests but the actual, rather than surrogate, fuels. SPK scaling factors are based on preliminary experimental results that should be updated with forthcoming measurements such as those from the Alternative Aviation Fuel Experiment (Anderson 2009). ULSJ scaling factors are based on an analytical examination of fuel properties.

5.1 Unburned Hydrocarbons, Carbon Monoxide, Nitrogen Oxides

For both ULSJ and SPK fuels, it was assumed that the emissions of CO, HC and NO_x were unchanged on a per kilogram of fuel basis. For ULSJ, this was based on the similarity of fuel composition to conventional Jet A. For SPK, this was based on a paucity of experimental data, though preliminary results indicate there is a change as discussed below. Therefore, the emissions of HC, CO and NO_x were scaled only with fuel use for both ULSJ and SPK fuels:

$$E_{AC-Alt-p} = \Delta_{alt} \cdot E_{AC-Jet-p}$$

Equation 8

where

$E_{AC-alt-p}$ is the total aircraft emissions inventory for an alternative fuel,

p is the pollutant considered (HC, CO or NO_x),

Δ_{Alt} is the fuel use scaling factor from Table 3 and

$E_{AC-Jet-p}$ is the total aircraft emissions inventory for Jet A.

Although there are not yet studies specifically focused on NO_x and HC emissions, there is preliminary data indicating reductions for both using SPK fuels. Testing of a Pratt & Whitney 308 engine using a 100% F-T SPK fuel shows a 60% reduction in HC as can be seen in Figure 8. There is also preliminary data indicating that there may be 5-10% reductions in NO_x emissions; however, these results were within experimental uncertainty (Miake-Lye and Timko 2008). This is again preliminary data based solely on one study and therefore it was not included in the current study. As more data, such as the Alternative Aviation Fuels Experiment results, are published, these scaling relationships should be updated.

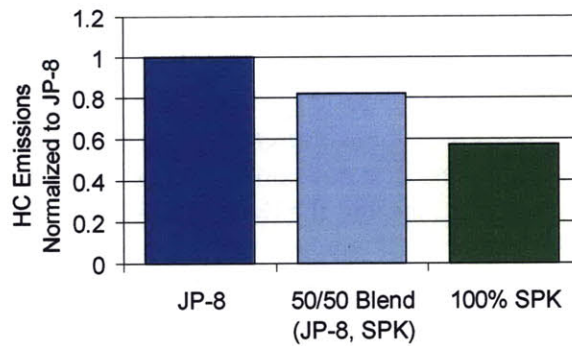


Figure 8 Unburned Hydrocarbon Emissions for a Pratt & Whitney 308 Engine (Timko et al. 2008)

5.2 Sulfur Dioxides

Mirroring the GSE, aircraft sulfur dioxide emissions scale linearly with fuel sulfur content, however, the sulfur content of jet fuel varies. A 2009 Coordinating Research Council (CRC) report surveyed refineries in the United States to record average Jet A sulfur values (Coordinating Research Council 2009). The sulfur content of Jet A is limited to 3,000 ppm sulfur; however, the average sulfur content of United States Jet A is typically below this value as can be seen from the average monthly CRC data in Figure 9. The highest individual fuel sulfur content value recorded by CRC was 2,200 ppm and the lowest was 2 ppm.

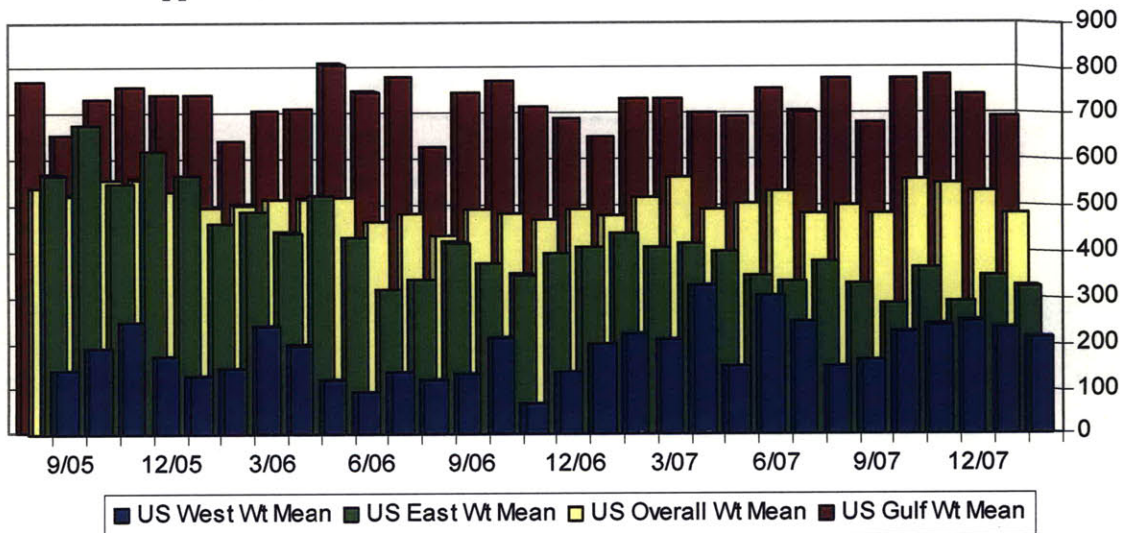
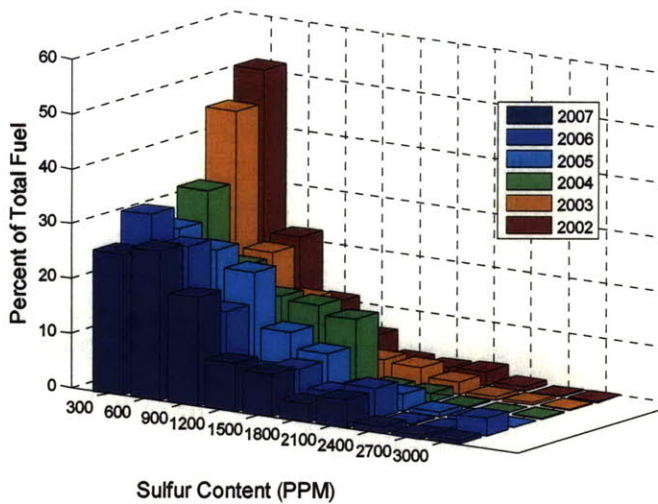


Figure 9 CRC Reported Jet A Fuel Sulfur Contents

In addition to the CRC data, the Defense Energy Support Center (DESC) also maintains a database of US Military jet fuel properties (Defense Energy Support Center 2006). DESC surveys military JP-8 worldwide. The distributions shown in Figure 10 demonstrate the variation in fuel sulfur content across samples and years. For example, in 2006, a nontrivial sample of fuel had sulfur content greater than 3000 ppm despite a weighted mean of 762 ppm. These distributions were not revealed in the CRC data as only aggregate data were reported.



	Weighted Mean	Weighted Standard Deviation
2002	530	514
2003	580	525
2004	666	504
2005	668	581
2006	754	648
2007	762	590

Figure 10 JP-8 Fuel Sulfur Content as Reported By PQIS (DESC, 2002-2007)

As seen in Table 19 and Figure 10, the overall US weighted means of the CRC and DESC samples for 2006 and 2007 were within 110 ppm; however, the individual region averages were not. EDMS, which was used to create the baseline emissions inventories in this study, uses a single fuel sulfur content of 680 ppm.

Table 19 Weighted Mean Fuel Sulfur Contents in PPM for 2006 and 2007 for Jet A (Coordinating Research Council 2009)

Year	2006	2007
US East	446	321
US Gulf	858	800
US West	240	395
Overall US	709	677

As with the GSE, aircraft sulfur emissions were scaled linearly according to fuel sulfur content:

$$E_{AC-Alt-SO_x} = \Delta_{Alt} \cdot E_{AC-Jet-SO_x} \cdot 0.022$$

Equation 9

where

$E_{AC-Alt-SO_x}$ is the total aircraft SO_x inventory for an alternative fuel,
 $E_{AC-Jet-SO_x}$ is the total aircraft SO_x inventory for Jet A and
 0.022 is the ratio of sulfur contents, 15/680.

5.3 Primary Particulate Matter

Particulate matter emissions were calculated according to the First Order Approximation (FOA) methodology. FOA was developed by the FAA's Office of the Environment in response to a need for a scientifically based methodology to estimate primary particulate matter; prior to FOA, emissions were based on a small number of aircraft tests or diesel

particulate matter emissions estimates (Ratliff 2007). EDMS uses a conservatively modified form of the third version of FOA (FOA3a). A complete discussion of the evolution and methodology behind the FOA methodology can be found in Ratliff (2007).

The FOA methodology speciates primary particulate matter into volatile and nonvolatile components. The nonvolatile component (PMNV) refers to the solid particulate component. PMNV is a result of incomplete combustion and is also referred to as soot, hard particles, black carbon, or elemental carbon. The volatile component of aircraft particulate matter comes from the condensation of volatile compounds in the exhaust plume. Volatile particulate matter is broken into three categories, particulate matter from sulfur (PMS), particulate matter from unburned fuel organics (PMFO) and particulate matter from lube oil (PMLO). The sum of each of these components reflects the full primary particulate matter emissions:

$$E_{AC-PM} = E_{AC-PMNV} + E_{AC-PMS} + E_{AC-PMFO} + E_{AC-PMLO}$$

Equation 10

The scaling for the first three components is discussed independently below. The quantity of lube oil and corresponding PMLO is assumed to be unchanged with fuel composition.

5.3.1 Primary Particulate Matter from Nonvolatile Compounds

The FOA3 and FOA3a calculations of nonvolatile particulate matter (PMNV) are based on the ICAO smoke number and air-to-fuel mass ratio of an aircraft engine. The smoke number is a measurement of soot and determined experimentally. Unlike FOA3, FOA3a is designed to be conservative and multiplies the flow rate by the engine bypass ratio in order to increase PMNV mass; on a fleet-wide basis, this increases PMNV mass by up to a factor of 8.6 (Sequeira 2008).

For ULSJ, it is conceivable that there could be reductions in PMNV as a result of reduced aromatic compounds due to the hydrodesulfurization process; however, data used by the EPA for the ULSD rulemaking indicate that aromatic compounds were not significantly (<10% reductions) affected by the hydrodesulfurization process. This data is attached in Appendix C (Smith and Environmental Protection 2009). For this study, it is assumed that ULSJ has the same aromatic content as conventional jet fuel and it will have the same emissions of PMNV per unit of fuel consumed:

$$E_{AC-ULSJ-PMNV} = \Delta_{ULSJ} \cdot E_{AC-Jet-PMNV}$$

Equation 11

where

$E_{AC-ULSJ-PMNV}$ is the scaled PMNV emissions for ULSJ and

$E_{AC-Jet-PMNV}$ is the initial PMNV emissions inventory for Jet A.

Turbine testing using an F-T jet fuel, however, has shown decreases in PMNV (Corporan et al. 2007; Timko et al. 2008; Whitefield 2008). This was expected as SPK fuels lack aromatic compounds. Data were collected from four different types of gas turbine engines with varied combustor technologies to explore changes in PMNV. These gas turbine engines included a turboshaft helicopter gas turbine (T63), a low bypass ratio

engine with older combustor technologies from the B52 (TF33), the Pratt and Whitney 308 engine (PW 308) and a higher bypass ratio engine with a modern combustor design used in the Boeing 737 (CFM56). Two PW 308 data sets were recorded from the same test using different testing techniques.

As shown in Figure 11 and Figure 12, which show PMNV reductions as a function of engine thrust for a 100% SPK fuel and a 50-50 blend of SPK with conventional jet fuel, respectively, each of these different combustor designs experience reductions in PMNV with the use of SPK. As can be seen in Figure 11 and Figure 12, emission reductions are generally greater at reduced thrust settings as compared to higher thrust settings and the pure SPK yields greater PMNV reductions.

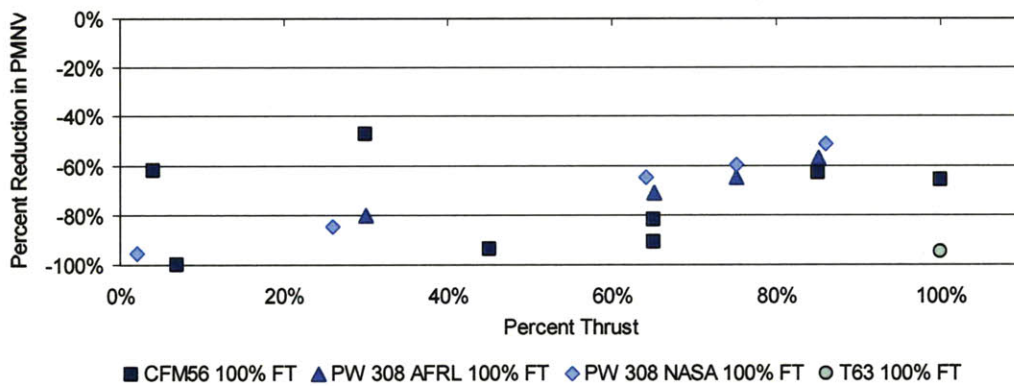


Figure 11 Reduction in PMNV Mass for Gas Turbine Combustion of 100% SPK as a Function of Thrust Setting (Corporan et al. 2007; Timko et al. 2008; Whitefield 2008)

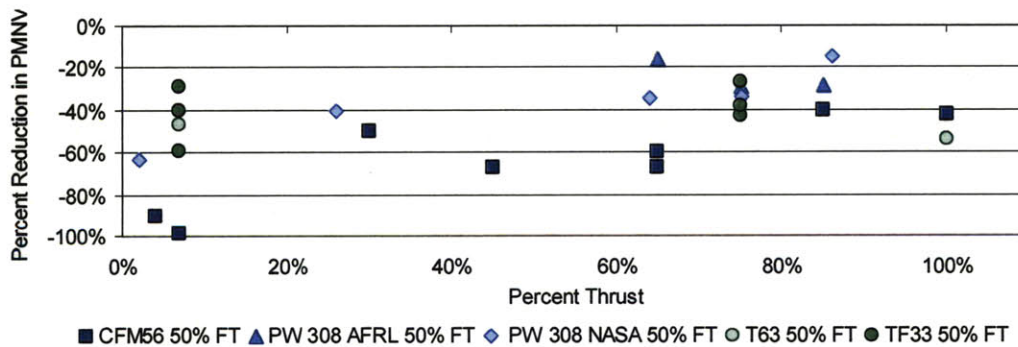


Figure 12 Reduction in PMNV Mass for Gas Turbine Combustion of a 50/50 Blend of SPK with Conventional Jet Fuel as a Function of Thrust Setting (Corporan et al. 2007; Timko et al. 2008; Whitefield 2008)

Within Figure 13 and Figure 14, least-squares fit lines were constructed for both the 50% and 100% SPK tests for the CFM56 and PW308 data. Note that the CFM56 data was modified to exclude two outlier points at 4% and 30% thrust and the curve fit was constrained to a maximum 100% reduction in PMNV. The data for these engine types were examined in greater detail as they are more representative of the commercial aircraft fleet.

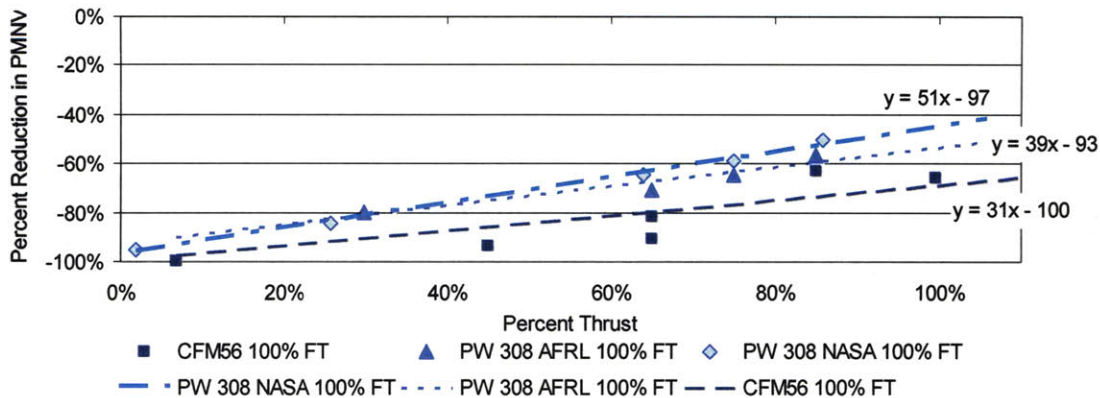


Figure 13 PMNV Reduction Curve Fits for 100% SPK

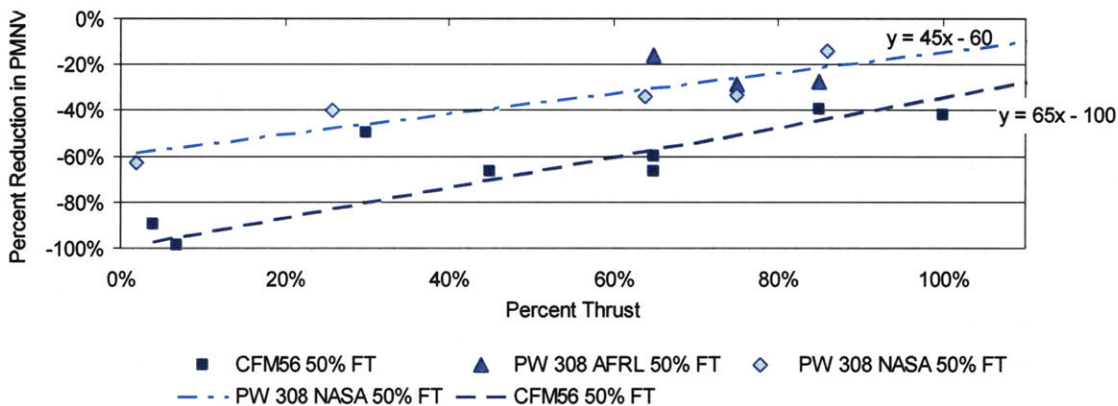


Figure 14 PMNV Reduction Curve Fits for 50-50 Blend of SPK and Conventional Jet Fuel

These curve fits were used to calculate PMNV reductions at each of the thrust settings in the landing takeoff (LTO) cycle. The final scaling factor was calculated using these reductions and weighted by the total fuel burn in each stage (taxi/idle, climb-out, takeoff, approach). The fuel burn was calculated using the average time in mode and thrust from ICAO Annex 17 and the fuel burn at each corresponding thrust point from the ICAO engine databank (ICAO 2008; ICAO 1993). The time in mode, fuel burn, and weighting for the CFM56 data are shown below in Table 20.

Table 20 Time in Mode and Fuel Use During the LTO Cycle for a CFM56 Engine (ICAO 1993)

Stage	Time in Mode (s)	Thrust (%)	Fuel Flow (kg/s)	Fuel Burn (kg)	Weighting
Take-Off	42	100	1.000	42	10%
Climb Out	132	85	0.836	110	27%
Approach	240	30	0.304	73	18%
Taxi/Idle	1560	7	0.114	177	44%

The engine specific reductions in PMNV for the LTO cycle are shown in Figure 15. The 100% F-T jet fuel PMNV reductions range from 76% to 86% while the 50-50 blend shows a broader range of reductions, from 42% to 69%. An average value for the AFRL PW 308 50-50 blend was not included because the highest reductions occurred at the low power settings and AFRL data does not include measurements at thrusts lower than 65%.

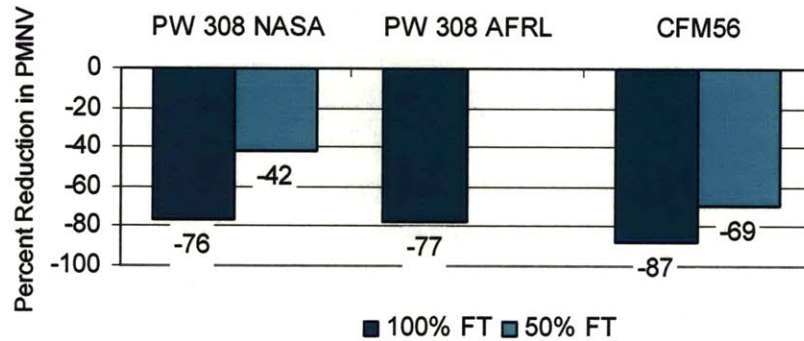


Figure 15 Engine Specific PMNV Reductions for LTO Cycle (Timko et al. 2008)

The relatively tight range of values for 100% SPK within Figure 15 should not be interpreted as meaning the fleet wide reduction in PMNV is well known. Different combustor technologies may produce varied reductions in PMNV and the measurements still contain uncertainty. As can be seen in, Figure 16 there was considerable uncertainty in the CFM56 emissions measurements at lower thrust settings with 100% F-T fuel. For example, in the 100% SPK test, there is a 38% difference in reduction between the 7% thrust and 9% thrust settings. As can be seen in Table 20, 44% of the weighting is placed on the 7% thrust setting.

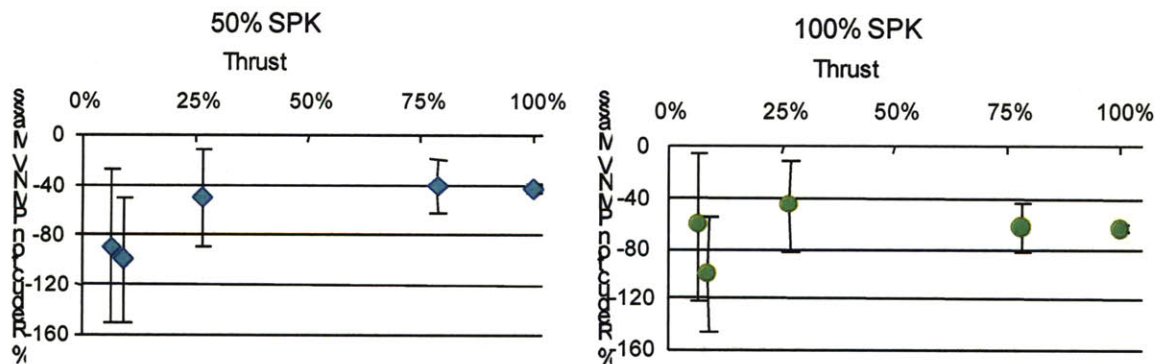


Figure 16 CFM56 Engine PMNV Testing Results Using SPK (Whitefield 2008)

The scaling used in this study was based on the PW 308 data provided by NASA as recommended by experts in the field, Dr. Miake-Lye and Dr. Timko from Aerodyne Research, Inc., because the PW 308 NASA data has smaller uncertainty bands and it used an improved testing methodology (Miake-Lye and Timko 2008). Once they are published, PMNV measurements from more recent tests, such as the AAFEX campaign, should be used to augment these data.

5.3.2 Primary Particulate Matter from Fuel Organic Compounds

FOA3 and FOA3a use the same general methodology to calculate the fuel organic portion of particulate matter, PMFO. The methodology is based on the emissions of unburned hydrocarbons (HC). The methodology also relies on the emissions testing from a CFM-56 aircraft engine to establish the ratio between sulfur and non-sulfur primary particulate matter:

$$EI_{PMFO} = \frac{T}{EI_{HC-CFM56}} EI_{HC-Engine}$$

Equation 12

where

- EI_{PMFO} is the emissions index in mg PMFO per kg fuel,
- T is the ratio between sulfur and non-sulfur primary particulate matter for the CFM-56,
- $EI_{HC-CFM56}$ is the emissions index for HC in the CFM-56 and
- $EI_{HC-Engine}$ is the HC emissions index for the engine considered.

The FOA3a methodology follows the same equation as above but it uses explicitly conservative assumptions in the analysis of the CFM-56 data.

For both SPK and ULSJ, it was assumed that there is no change in PMFO. As indicated above, preliminary data indicate a change in unburned hydrocarbons, however the data is a result of only one study, and these data are still being analyzed by researchers (Miakel-Lye and Timko 2008).

5.3.3 Primary Particulate Matter from Sulfur Containing Compounds

FOA calculates the particulate matter resulting from sulfur as a function of the fuel sulfur content and a conversion from elemental sulfur to sulfuric acid (Ratliff 2007):

$$EI_{PMS} = 10^6 \left(\frac{FSC \cdot \varepsilon \cdot MW_{out}}{MW_S} \right)$$

Equation 13

where

- EI_{PMS} is the emissions index in mg PMS per kg fuel,
- FSC is the fuel sulfur content percent,
- ε is the sulfur to sulfuric acid conversion rate (percent),
- MW_{out} is 96 (FOA3) or 98 (FOA3a) the molecular weight of the hydrated sulfates (H_2SO_4 and H_2O) in the exhaust and
- MW_S is 32, the weight of elemental sulfur.

As shown in Equation 13, PMS creation is linear with fuel sulfur content. Therefore, the PMS inventory for both SPK and ULSJ was scaled linearly:

$$E_{AC-Alt-PMS} = \Delta_{Alt} \cdot E_{AC-Jet-PMS} \cdot 0.022$$

Equation 14

where

$E_{AC-Alt-PMS}$ is the total aircraft PMS inventory for an alternative fuel,
 $E_{AC-Jet-PMS}$ is the total aircraft PMS inventory for Jet A and
0.022 is the ratio of sulfur contents, 15/680.

This scaling used the EDMS fuel sulfur content of 680 ppm for Jet A and 15 ppm for both ULSJ and SPK.

Chapter 6: Air Quality Modeling

The primary health concern relating to emissions from aviation is the inhalation of fine particulate matter (PM_{2.5}). Particulate matter, as explained in Chapter 2, can be divided into primary and secondary components. Although inventory scaling illuminates the changes in primary particulate matter and gaseous precursors to secondary particulate matter, it does not capture the end changes in ambient particulate matter concentration. Capturing these changes in concentration, which ultimately affect human health, requires a full atmospheric chemistry model.

To demonstrate the changes in concentration and changes in emission inventories, the Hartsfield-Jackson Atlanta Airport, located in Atlanta, Georgia, was modeled. The Hartsfield-Jackson Atlanta International Airport (ATL) was chosen for its size, its location in a nonattainment area for PM_{2.5} and ozone (Environmental Protection Agency 2008), and importantly to leverage previous research efforts. ATL is the busiest airport in the world; according to Airports Council International, 89 million passengers passed through ATL in 2007, more than 12 million more than the second busiest airport, Chicago O'Hare (Airports Council International 2009).

In order to model the changes in pollutant concentrations, a series of three programs was used. First, EDMS was used to create an emissions inventory for aircraft and GSE. Second, the emission inventories were reformatted in SMOKE (Sparse Matrix Operator Kernel Emissions). Third, the reformatted emissions inventories were combined with a dispersion model, an atmospheric chemistry model, background inventories and meteorological conditions in CMAQ (Community Multiscale Air Quality modeling system). Finally, the CMAQ output was processed using the EPA program MATS (Modeled Attainment Test Software). MATS adjusts the CMAQ outputs to be consistent with levels of pollutants measured at air quality monitoring sites and adds the particle bound water to the ionic concentrations computed by CMAQ.

This work examined four different fuel scenarios at ATL. The first scenario modeled the aircraft emissions with Jet A and GSE emissions with ULSD. This first scenario modeled the airport as it will be operating in 2011 when the ULSD standard comes into full effect. The second scenario was a low sulfur scenario with aircraft using USLJ and GSE using USLD. The third scenario considered a potential single-fuel airport with both GSE and aircraft using a 50-50 blend of SPK and ULSJ. Finally, the fourth scenario considered a low emissions case with GSE producing no emissions (for example being converted to all electric or fuel cell) and aircraft burning 100% SPK fuel. These scenarios are summarized in Table 21.

Table 21 Fuel Scenarios Modeled for ATL Emissions Inventory Analysis

Fuel	Aircraft	GSE
Scenario 1	Jet A	ULSD
Scenario 2	ULSJ	ULSD
Scenario 3	50-50 Blend SPK-ULSJ	50-50 Blend SPK-ULSJ
Scenario 4	100% SPK	-

Due to the uncertainty in the GSE inventories, as will be discussed below, only the aircraft emissions in the four scenarios were analyzed with the full air quality model.

6.1 EDMS Inventory

As mentioned previously, the ATL aircraft emissions inventory used in this work was leveraged from previous work performed under PARTNER Project 16 using EDMS and SMOKE (Arunachalam et al. 2008). This inventory included only ICAO certified jet engines; again, no APUs or piston aircraft were included, and a four kilometer grid size was used to examine the relative impact of aircraft from ATL on the region. The 2002 aircraft flight schedule for June and July was used for the air quality modeling while full annual emission were used for inventory analysis.

6.1.1 Modifications to EDMS

Within EDMS, the model year was set to 2011. The model year dictates the pollution control technology and sulfur content of diesel fuel as shown in Table 14. 2011 was used in order to force a low sulfur fuel content for the GSE; using an earlier year with high fuel sulfur content would overstate the benefits of alternative fuels. An alternative jet fuel will not realistically be available while the high sulfur content diesel fuel is in use; therefore, the reductions in SO_x would be overstated. For the inventory scaling, the full annual inventory for both GSE and aircraft was used.

Although they were discussed in Chapters 4 and 5, the unburned hydrocarbon emissions for GSE and aircraft at the gate were not examined in the air quality modeling. The aircraft HC emissions were not included due to a lack of appropriate chemical speciation profiles. The GSE HC emissions were not included due to inability to convert from the specific EDMS output species (TOG, VOC, NMHC) to the generalized HC measured in the engine studies discussed in Chapter 4. Because of the relatively small volumes of HC being produced, the effect of neglecting these emissions on ambient PM_{2.5} concentrations was expected to be negligible.

Standard EDMS emissions inventories cover a radius of 20km around the airport and extend to a maximum height of 10,000 feet; however, for PARTNER Project 16, a larger 80km radius was used. This larger radius was used to include emissions from aircraft that do not reach 10,000 feet within 20km; this is illustrated in Figure 17. The dashed line indicates a flight path that does not reach 10,000 feet within 20km laterally but does reach 10,000 feet within 80km laterally.

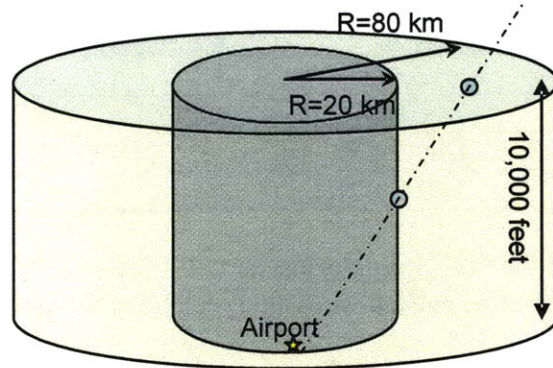


Figure 17 Illustration of Aircraft Not Reaching Mixing Height in 20km Radius

6.1.2 EDMS GSE Inventory

The GSE emissions inventory was created with EDMS using the ATL aircraft schedule. As discussed in 4.1, EDMS is capable of creating a GSE emissions inventory with only an aircraft schedule as the user input. The adequacy of this model was unknown, so comparison to a partial GSE inventory from Delta Airlines was made.

For ATL, EDMS models 684 individual GSE, 445 of which have diesel engines. Because EDMS does not record emissions for individual GSE, the emissions cannot be scaled on a unit-by-unit basis. Instead, it was assumed that the proportion of GSE emissions from diesel GSE was directly related to the number of GSE. Although diesel GSE comprise approximately 66% of the total GSE inventory by fuel type, as seen in Figure 18, electric GSE are not responsible for any emissions at the airport. Therefore, the emissions were only divided between the gasoline and diesel powered GSE. Of this portion, diesel GSE made up 78%.

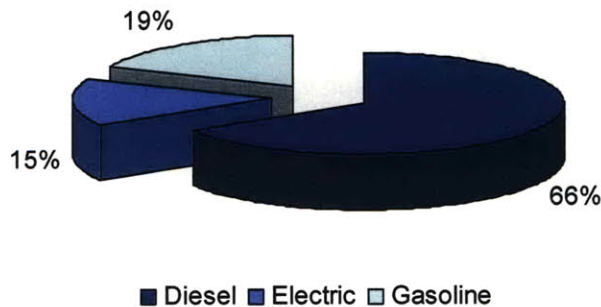


Figure 18 Ground Support Equipment by Fuel Type

Unlike the aircraft flight schedule, which provided actual flights and aircraft used, the GSE vehicle inventory was produced by an internal EDMS algorithm as discussed in 4.1 and 6.1.2. Although the actual GSE vehicle inventory for all of ATL was not publicly available, the GSE inventory for Delta was provided for analysis (Webb 2008). Since Delta is responsible for approximately 50% of the combined cargo and passenger operations at ATL (Airports Council International 2009), this fraction was assumed to be representative of the whole airport.

The Delta GSE vehicle inventory differed from the EDMS inventory both in composition and number. The Delta vehicle inventory contained 2,251 individual pieces of equipment compared to the EDMS vehicle inventory, which had 684. The Delta vehicle categories were mapped into the EDMS categories as shown below in Table 22. When no matching category was found the EDMS category was designated as */not included*. There were 372 vehicles in the Delta GSE fleet that do not have a corresponding EDMS category.

Table 22 Mapping of Delta Vehicle Categories to EDMS GSE Categories

Delta Category	EDMS Category	Delta Category	EDMS Category
Aerial Platform	<i>/not included {27}</i>	Maintenance Boom	<i>/not included (DefStan91-91)</i>
Air Conditioning	<i>Air Conditioner</i>	Misc Elec Cart	<i>Cart</i>
Air Start	<i>Air Start</i>	MTC Lift Truck	<i>Lift</i>
Aircraft Tow Tractor	<i>Aircraft Tractor</i>	MTC Van	<i>/not included {5}</i>
Auto Fuel Unit	<i>Fuel Truck</i>	Pallet Truck	
Automobile	<i>/not included {17}</i>	Passenger Steps	<i>Passenger Stand</i>
Baggage Tractor	<i>Baggage Tractor</i>	Pick Up Truck	<i>/not included {131}</i>
Belt Loader	<i>Belt Loader</i>	PSGR Elec Cart	<i>Cart</i>
Bus	<i>/not included {5}</i>	Scrubber	<i>Sweeper</i>
Cab SVC Lift Trucks		Scrubber/Sweeper	<i>Sweeper</i>
Cab SVC Van	<i>/not included {13}</i>	Service Truck	<i>Service Truck</i>
Cargo Tractor	<i>Cargo Tractor</i>	Sport Utility	<i>/not included {18}</i>
Cargo Van	<i>/not included {3}</i>	Stock Picker	<i>/not included {25}</i>
Container Loader	<i>Cargo Loader</i>	Super Tug	<i>Baggage tug</i>
Crane	<i>/not included {8}</i>	Sweeper	<i>Sweeper</i>
De-Ice Truck	<i>De-Icer</i>	Tractor	<i>/not included</i>
Farm Tractor	<i>/not included</i>	Truck	<i>/not included {35}</i>
Forklift	<i>Fork Lift</i>	Utility Vehicle	<i>/not included</i>
Ground Power	<i>Ground Power Unit</i>	Van	<i>/not included {67}</i>
Heater	<i>/not included {4}</i>	Water Service Cart	<i>Cart</i>
Lavatory Service Cart	<i>Cart</i>	Wrecker	<i>/not included</i>
Lavatory Service Truck	<i>Lavatory Truck</i>		

As can be seen below in Figure 19, there were also several categories for which vehicles exist in one vehicle inventory but not the other. For example, the EDMS inventory included 51 hydrant trucks while the Delta inventory contained none. One of the greatest disparities was that the Delta inventory contained 918 baggage tractors while the EDMS inventory contained 61. Within the baggage tractor category, the Delta inventory indicated that 58% of the baggage tractors were diesel powered while the EDMS inventory assumed that they all used gasoline. For some of the vehicle categories that were missing from the Delta inventory, such as catering trucks, it is likely that Delta outsources the task to an outside company and thus does not own or track the vehicles.

Although the differences in the gross number of vehicles between the two vehicle inventories could be compared, it was difficult to compare emissions inventories between

them because the manner of vehicle operation was unknown. For example, the vehicles in the EDMS inventory could be modeled as operating continuously throughout the day while the Delta inventory could contain units that are no longer operated or are only operated sporadically. Nonetheless, the differences in types of units indicated that the EDMS default modeling does not accurately capture the GSE population at ATL.

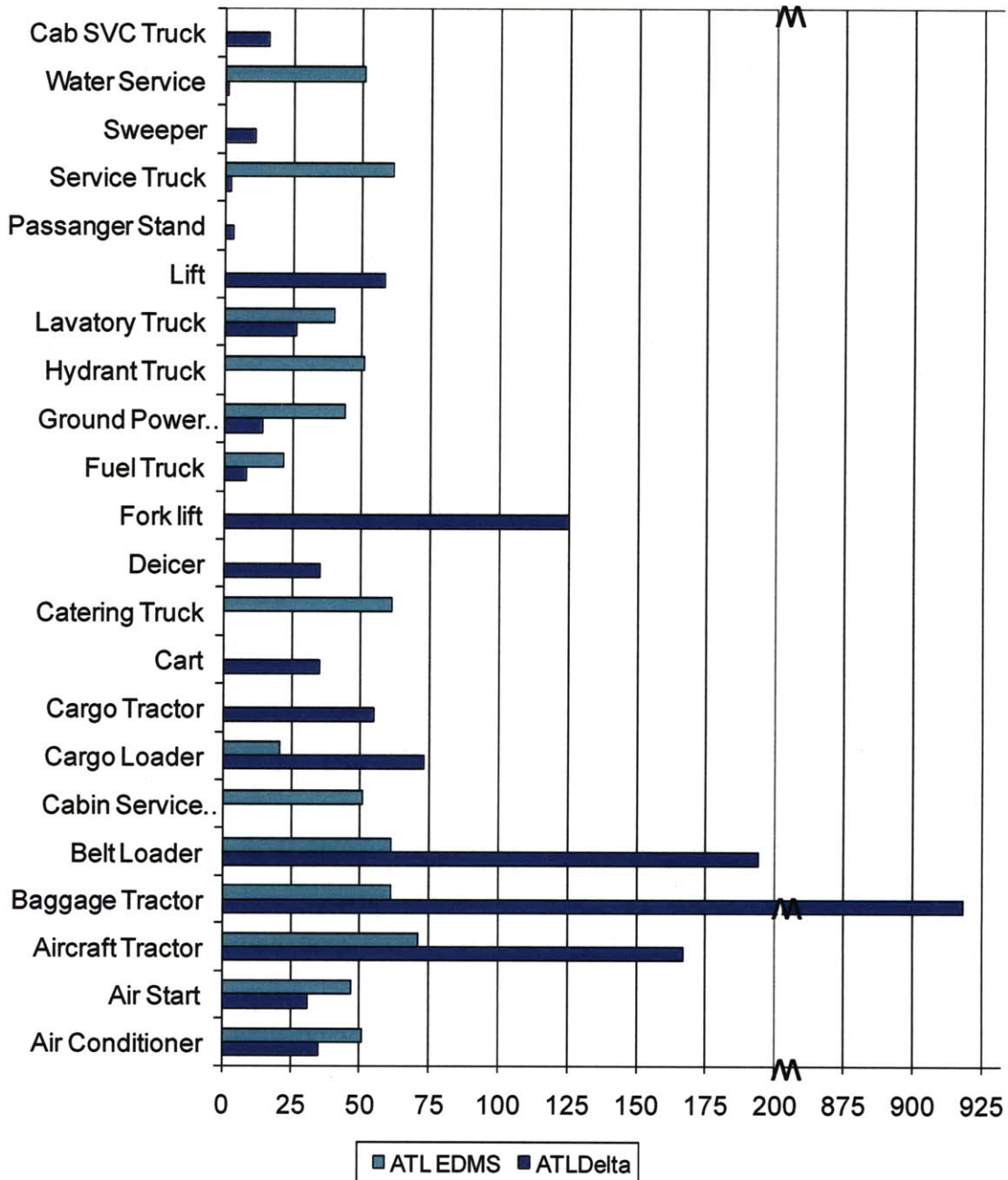


Figure 19 Delta and EDMS GSE Vehicle Inventories

The number of baggage tractors, 918, in the Delta inventory exceeds the range covered in the chart.

Due to the discrepancies, in vehicle inventories, a rudimentary check was conducted on the total GSE fuel consumption. Although EDMS does not calculate fuel burn, there is a

linear relationship between SO_x emissions and fuel burn as shown in Equation 5. Because the EF_{HC} term in Equation 5 can be considered negligible (less than 5% of the BSFC term for three vehicles that were spot-checked), Equation 5 simplifies to:

$$EF_{SO_x} = (BSFC \cdot 453.6 \cdot (1 - soxcnv)) \cdot 0.01 \cdot soxdsl \cdot 2$$

Equation 15

The total SO_x produced is thus the sum of the emission factor multiplied by the time of use, load factor and horsepower for each unit of GSE as described in Equation 1. These three terms, the load factor, horsepower, and time of operation determine the total fuel burn were assumed to remain constant. Therefore, Equation 1 could be rewritten with Equation 15 as:

$$SO_2 = FuelBurn \cdot (1 - soxcnv) \cdot 0.01 \cdot soxdsl \cdot 2$$

Equation 16

where

SO₂ is the total grams of SO₂ produced by the diesel engine portion of the GSE fleet and

Fuel Burn is the total grams of diesel fuel consumed.

This can be solved for fuel burn as:

$$FuelBurn = \frac{grams(SO_x)}{(1 - soxcnv) \cdot 0.01 \cdot soxdsl \cdot 2}$$

Equation 17

According to EDMS the total mass of SO_x produced by the diesel GSE at ATL based on the 2002 aircraft schedule is 7,500 grams. Using Equation 17, the total fuel burn is 198 million kilograms or approximately 61 million gallons. Based on his analysis of fuel use at several US commercial airports, Webb (2009) estimates GSE diesel fuel use of 0.25-0.30 gallons per enplaned passenger. This would result in 9.6-11.6 million gallons of fuel based on 36,639,600 enplaned passengers at ATL in 2002 (Hartsfield-Jackson Atlanta International 2008). This represents a potential factor of six difference in fuel use and emissions between the EDMS methodology and an independent estimate of GSE fuel use. Due to this uncertainty as well as the uncertainty associated with both the NONROAD model and the scaling factors, GSE were not included in the full air quality model.

6.2 SMOKE Processing

The emissions inventories that were developed in EDMS were prepared for use in CMAQ using a series of scripts known as SMOKE (Sparse Matrix Operator Kernel Emissions) (CMAS 2008). SMOKE is able to process area, point, biogenic and mobile emission inventories. It is designed to speciate inventories into pollutants required by air quality programs, assign emissions to grid cells, allocate emissions temporally if required, merge weather data with emissions inventories and create formatted output

files. SMOKE version 2.5 was used for this study. A summary of model settings can be found in Table 23.

Table 23 SMOKE Version 2.5 Settings

Item	Setting
Grid	EastUS4_126x153 (4km)
Grid Projection	Lambert Conformal Conic
Mechanism	cb05cltx_ae4_aq
Flow Rate Factor	15878
Pollutant Conversion	No
Rep Layer Max	23

6.3 CMAQ Modeling

The ambient particulate matter concentrations were computed from the speciated emissions inventories using CMAQ (Community Multi-scale Air Quality model), an EPA developed, three-dimensional, Eulerian chemical-transport model (Byud and Schere 2006). The model has three main components: a meteorological model system, an emissions model and a chemistry-transport modeling system. For each time step and grid cell, CMAQ calculates the change in chemical concentration based on advection, diffusion, chemical formation, removal of each species and the given emissions. CMAQ contains five separate processors: the Initial Conditions Preprocessor (ICON), Boundary Conditions Preprocessor (BCON), Clear-Sky Photolysis Rate Calculator (JPROC), Meteorology-Chemistry Interface Program (MCIP) and the CMAQ Chemistry-Transport Model (CCTM). For this work, ICON, BCON, JPROC and MCIP data sets were provided from previous work and only the CCTM module was run independently (Arunachalam et al. 2008). CMAQ version 4.6 was used for this modeling. A full set of CCTM settings, mechanisms and sample run script is provided in Appendix D.

6.4 MATS Processing

The CMAQ output was scaled to be consistent with monitor measurements and corrected for errors in monitor data using the SANDWICH method (Sulfate, Adjusted Nitrate, Derived Water, Inferred Carbon Hybrid) using MATS (Model Attainment Test Software), an EPA developed program. MATS models ambient particulate matter concentrations, visibility and ozone attainment (Environmental Protection 2008). It also apportions particle bound water mass to the ionic compounds. MATS was run using default monitor data and monitor data deletions, non-gradient corrected spatial fields and default EPA specifications except where noted. Non-default settings for MATS are shown below in Table 24.

Table 24 MATS Non-Default Model Settings For All Runs

Item	Setting
Baseline and Forecast Output	Interpolate Monitor Data to FRM Monitor Sites
IMPROVE Monitor Data Years	2002
PM _{2.5} Monitor Data Years	2001-2003
NH ₄ Future Calculation	Base Year NH ₄ and RRF

Unlike the CMAQ output, the MATS output concentration includes a column for particle bound water. In order to partition the particle bound water and ammonium into ammonium nitrates and ammonium sulfates, MATS results were aggregated using Equation 18 and Equation 19, based on EPA guidance (Sequeira 2008).

$$\text{Concentration_Ammonium_Nitrates} = 1.29 * 1.12 * \text{Concentration_NO}_3$$

Equation 18

$$\text{Concentration_Ammonium_Sulfates} = \text{Concentration_SO}_4 + \text{Concentration_NH}_4 - 0.29 * \text{Concentration_NO}_3 + \text{Concentration_H}_2\text{O} - 0.12 * 1.29 * \text{Concentration_NO}_3$$

Equation 19

Chapter 7: Air Quality Modeling Results

This chapter presents the results of the emissions inventory scaling for both GSE and aircraft, the results of the CMAQ analysis across fuel scenarios and the processing of the CMAQ results in MATS. A brief comparison of the FOA3 and FOA3a aircraft primary particulate matter components is also included.

7.1 Ground Support Equipment Emissions Inventory

The GSE inventory was scaled according to the equations presented in Chapter 4. The emissions inventory included full annual emissions with an ultra low sulfur diesel fuel. As discussed in 6.1.2, diesel engine GSE were assumed to emit 78% of the pollutants from all of the GSE.

Table 25 Scaled GSE Pollutant Inventories for the Fuels Being Considered (in kg)
Inventory includes diesel, gasoline, and electric powered GSE. PM denotes primary particulate matter.

	CO	NO _x	SO _x	PM
ULSD	3,500,000	380,000	7,500	12,000
ULSJ	2,500,000	330,000	7,500	7,100
50 / 50 SPK / ULSJ	2,500,000	340,000	7,500	7,100
100% SPK	2,400,000	340,000	7,500	7,100

The scaled GSE emissions are shown in Table 25. It is important to recall that F-T diesel fuel was used as a surrogate for SPK for the CO and NO_x emissions while JP-8 was used as a surrogate for SPK for the primary particulate matter emissions.

The 50/50 blend produced a 30% reduction in CO emissions from diesel engine GSE. This is the average of the 31% reduction in CO using 100% SPK shown in Table 25 and the 29% reduction emissions from ULSJ. The final CO reduction for the full inventory using the 50/50 blend was 24% as the diesel engine GSE were assumed to contribute 78% of the total GSE emissions. The 50/50 blend reduced NO_x emissions by 11%. This 11% overall reduction was a result of the diesel engine emissions from the use of SPK (13%) and ULSJ (16%), combined with 78% of the total GSE using the fuel blend. There was no reduction in SO_x emissions as a result of the fuel change to a 50/50 blend because ULSJ and SPK were assumed to have the same sulfur content, 15 ppm, as ULSD. Finally, the 50-50 blend produced a 41% reduction in primary particulate matter emissions, which is a result of the 52% reduction in PM emissions resulting from the use of either a jet fuel or an SPK fuel blend combined with 78% of the total GSE using the fuel blend.

7.2 Aircraft Emissions Inventory

The aircraft gas turbine emissions inventory was scaled according to the equations presented in Chapter 5. The baseline emissions inventory included full annual emissions with all aircraft burning Jet A with an assumed fuel sulfur content of 680 ppm.

As shown below in Figure 20, ULSJ, SPK and the 50/50 blend of SPK and ULSJ produced reductions in primary particulate matter. ULSJ primary particulate matter emissions, column three, were 37% lower than Jet A. SPK emissions were 72% lower, and the 50/50 blend emissions were 56% lower. These reductions were primarily a result of changes in PMNV and PMS as discussed in 5.3.1 and 5.3.3. The reduction in PMS was larger than that in PNNV in both percentage and absolute terms. As discussed in 5.3, PMLO, primary particulate matter resulting from lube oil, was assumed to be unchanged.

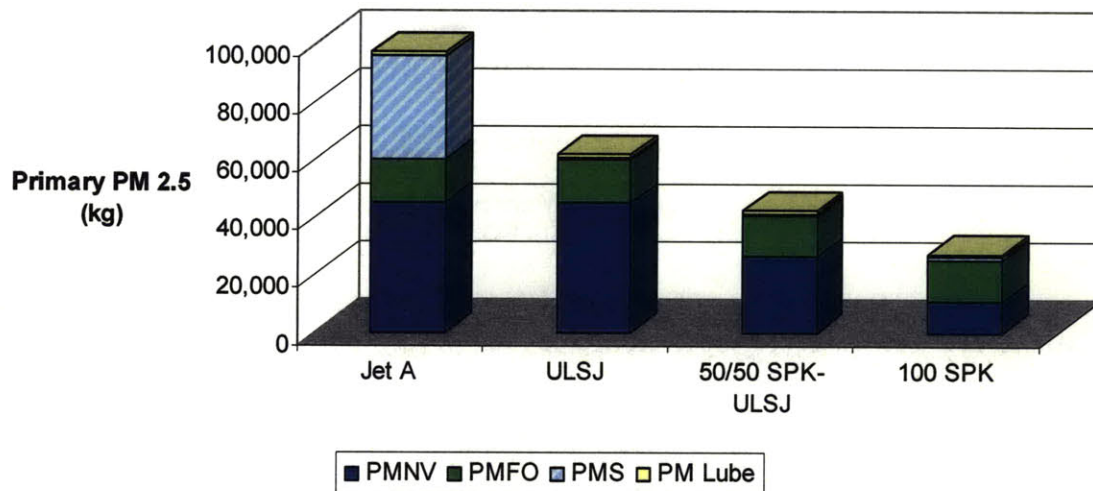


Figure 20 Scaled Aircraft Primary Particulate Matter Emissions, Broken Out by Species, Using EDMS with FOA3a

As discussed in 5.3, there are two FOA methodologies currently in use, FOA3 and FOA3a where FOA3a is an explicitly conservative version of FOA3. In order to demonstrate the differences in primary particulate matter scaling with these methodologies, an aircraft emissions inventory was created using the Federal Aviation Administration's "Aviation Environmental Design Tool (AEDT). The inventory contains ATL flights for the year 2006. The scaling, shown in Figure 21 is intended only to show the difference in composition and difference in scaling of emissions inventories from the two methodologies. The results presented in Sections 7.3 and 7.4 are based on the FOA3a results presented in Figure 38.

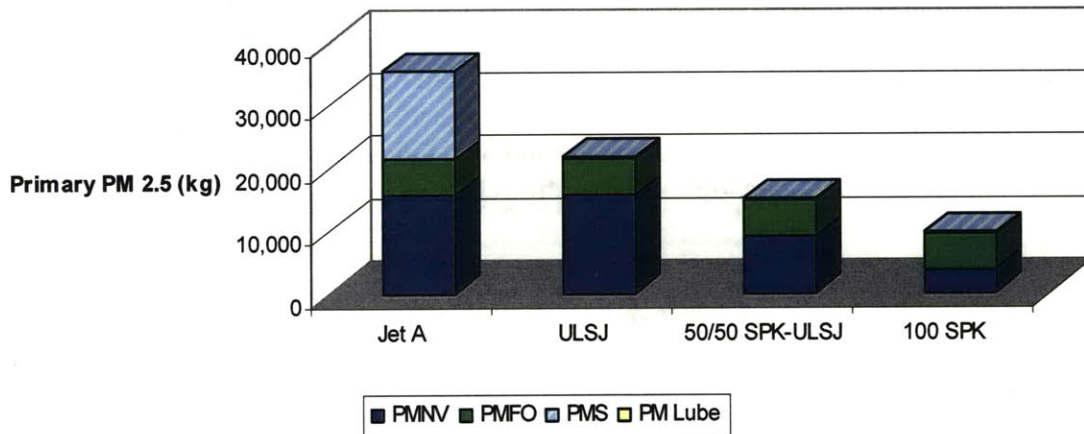


Figure 21 Scaled Aircraft Primary Particulate Matter Emissions, Broken out by Species, Using AEDT with FOA3

The composition of primary particulate matter from the FOA3 and FOA3a inventories are shown in Table 26. The relative percentage of each species were within 2% for PMNV, PMS and PMFO; FOA3 does not include lube oil. Prior work, (e.g., Ratliff et al. 2009) has shown a decomposition of primary particulate matter species that differs from those presented here. The underlying reason for the similarity here and the difference found elsewhere was not determined and it should be re-examined with additional analysis.

Table 26 Decomposition of Primary Particulate Matter Species Using FOA3 and FOA3a

% Total PM Composition	PMNV	PMS	PMFO
FOA3	45	39	16
FOA3a	47	37	15

Because of the similar relative primary particulate matter components in the FOA3 and FOA3a emissions inventories, there is a similar overall reduction in primary particulate matter when ULSJ and SPK scaling is applied. Using FOA3, there was a 38% reduction using ULSJ, a 57% reduction using a 50/50 blend and a 72% reduction using 100% SPK. As shown by the data in Table 27, these reductions for FOA3 and FOA3a were within 1% of one another.

Table 27 Comparison of Primary Particulate Matter Reductions Using FOA3 and FOA3a

% PM Reduction	ULSJ	50/50	SPK
FOA3	38	57	72
FOA3a	37	56	72

As discussed in Section 5.1, the changes in aircraft gas turbine NO_x and CO emissions were assumed to be only due to changes in fuel burn. The NO_x and CO emissions for ULSJ, shown in Table 28 are reduced by the 0.5% change in fuel burn. Because of the change in fuel use, the NO_x emissions for 100% SPK were reduced by 2.1%, and the 50/50 blend were reduced by 1.3%. For NO_x this scaling was conservative as preliminary

studies indicate that NO_x is reduced with SPK fuel use, as discussed in 5.1. The CO emissions for all four scenarios were within 2%.

The SO_x emissions from aircraft gas turbines were reduced in scenarios two, three and four as a result of the change in fuel sulfur content. The 98% reductions shown in Table 28 were a result of the change from 680 ppm to 15 ppm sulfur, as discussed in 5.2. The emissions for ULSJ, SPK and the 50/50 blend were also reduced as a result of the fuel changes discussed above and in Table 3.

Table 28 Scaled Aircraft Gas Turbine Emission Inventories For the Fuels Being Considered (in kg)
Note that PM denotes primary particulate matter.

	CO	NO _x	SO _x	PM
Jet A	5,900,000	6,500,000	680,000	97,000
ULSJ	5,900,000	6,400,000	15,000	62,000
50 / 50 SPK / ULSJ	5,800,000	6,400,000	15,000	42,000
100% SPK	5,800,000	6,300,000	15,000	27,000

7.3 Combined Aircraft and Ground Support Equipment Emissions Inventory

Figures 22-24 present the aircraft and GSE emissions from the scenarios discussed in Table 21. In scenario four, no GSE emissions were considered; this scenario may be thought of as a scenario with complete electrification of the GSE fleet.

In the emissions inventory analysis, aircraft were responsible for the vast majority of primary particulate matter emissions. As the aircraft primary particulate matter dropped for the ULSJ/ULSD case and the 50/50 SPK/ULSJ case, GSE primary particulate matter emissions rose to 16% (ULSJ/ULSD) and 14% (SPK/ULSJ) compared to 3% in the base case. The contributions of both aircraft and GSE to total primary particulate matter are shown in Figure 22. The uncertainty due to changes in fuel burn discussed in 6.1 is also reflected in Figure 22; reducing the fuel burn by a factor of six lowered GSE's contribution to primary particulate matter emissions in the base case to 2% of the total from 11%.

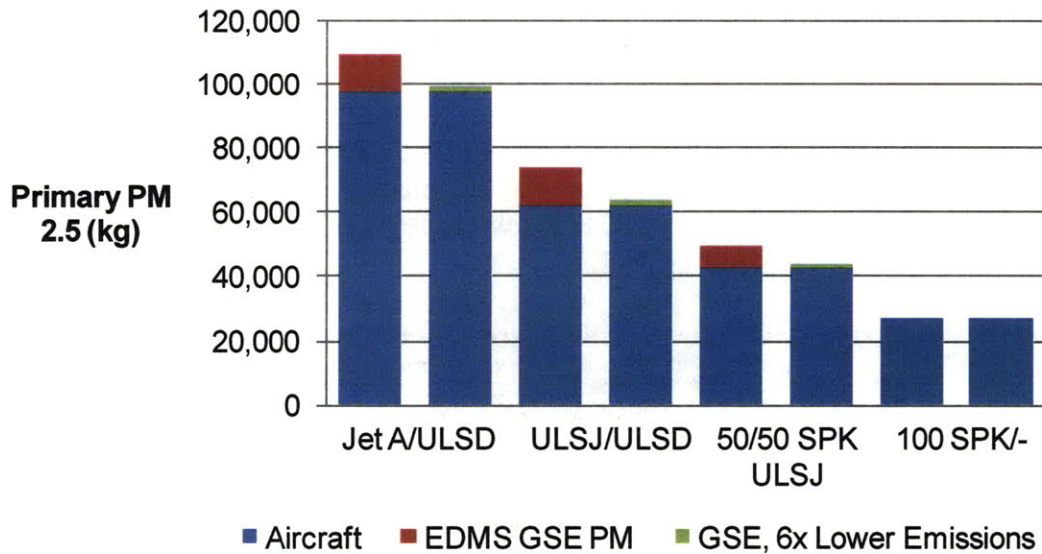


Figure 22 Scaled Primary Particulate Matter Emissions Inventory for Aircraft and GSE with Default EDMS Fuel Consumption and Modified GSE Fuel Burn, as Suggested by Webb (2009)

Aircraft were also responsible for the majority of secondary particulate matter precursors. Across all cases, GSE produced 6% or less of NO_x emissions (see Figure 23). In the base case with Jet A and ULSD, GSE produced only 1% of total SO_x emissions (see Figure 24). When the sulfur content of jet fuel was reduced in the ULSJ and 50/50 blend cases, GSE became responsible for 33-34% of total SO_x emission; however the overall amount of SO_x emissions from aircraft and GSE was reduced by 97%.

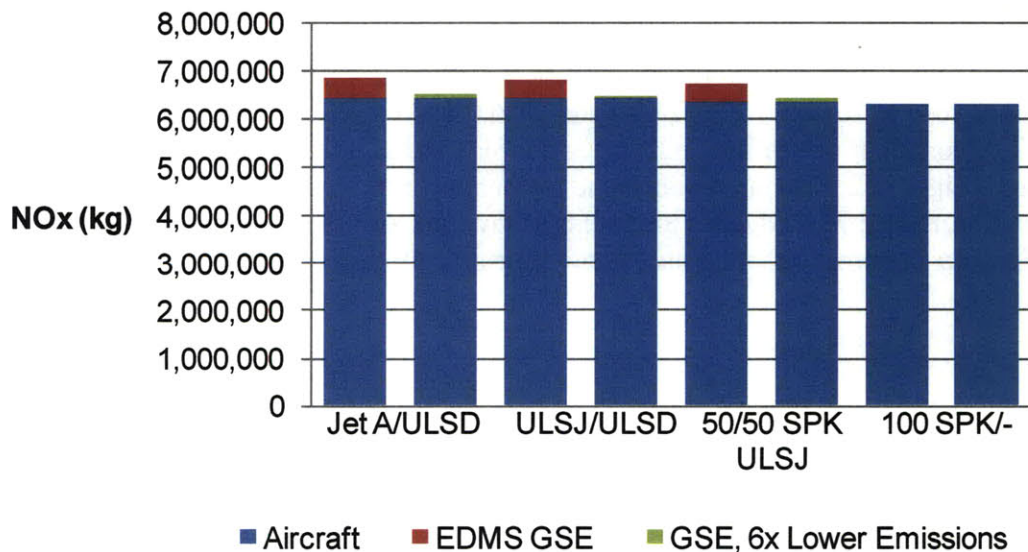


Figure 23 Scaled NO_x Emissions Inventory for Aircraft and GSE with Default EDMS Fuel Consumption and Modified GSE Fuel Burn, as Suggested by Webb (2009)

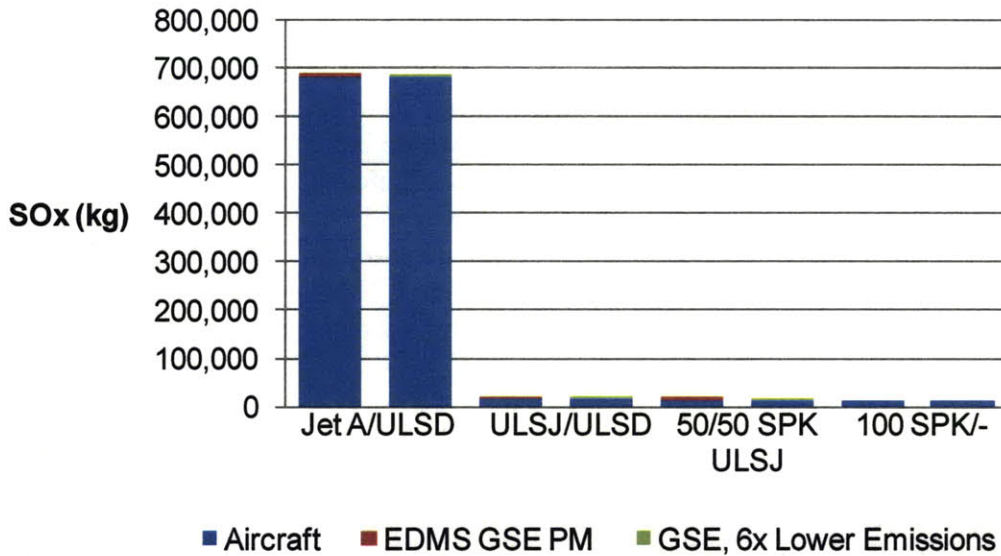


Figure 24 Scaled SO_x Emissions Inventory for Aircraft and GSE with Default EDMS Fuel Consumption and Modified GSE Fuel Burn, as Suggested by Webb (2009)

As shown in Figure 25, GSE were responsible for a larger percentage of CO than primary particulate matter, SO_x or NO_x. In scenarios one and two, GSE were responsible for 37% of all CO emissions. In scenario three, this reduced to 30% due to CO reductions from the SPK in the blend. As shown in the primary particulate matter example above and in Figure 25, if the GSE fuel usage were overestimated by a factor of six as suggested by the analysis contained in 6.1.2 these contributions would be considerably reduced. The CO emissions from aircraft were constant across scenarios except for the change in fuel use.

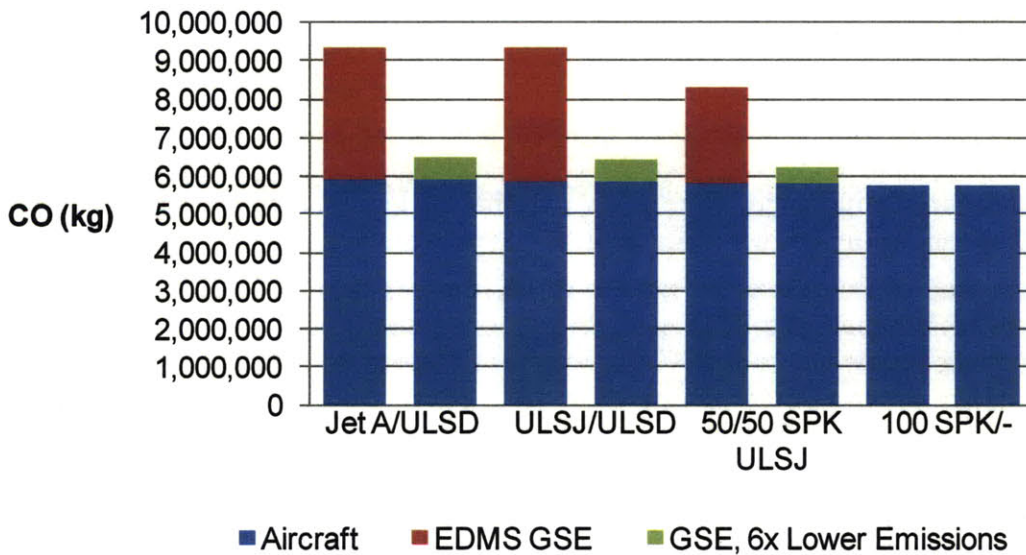


Figure 25 Scaled CO Emissions Inventory for Aircraft and GSE with Default EDMS Fuel Consumption and Modified GSE Fuel Burn, as Suggested by Webb (2009)

7.4 CMAQ Emission Concentration Results

The CMAQ results discussed in this section include only emissions from aircraft as discussed in 6.1. The output from CMAQ is a cell-by-cell concentration of six ionic compounds that comprise particulate matter; these six species combined give the total ionic ambient particulate matter concentration (which includes both primary and secondary contributions) in each grid cell. The six ionic components are ammonium, sulfates, nitrates, elemental carbon, organic carbon and crustal material; their corresponding CMAQ chemical output species are listed in Table 29. Also shown in column three of Table 29 are the translations of the CMAQ species names to the primary particulate matter components and gaseous secondary particulate matter precursors that were discussed in Chapter Five.

Table 29 PM_{2.5} Component Species and Constituent CMAQ Species
The letter I indicates a primary species while J indicates a secondary species.

PM _{2.5} Component	CMAQ Species Names	Aircraft PM Equivalent Inventory Species
Ammonium	ANH4I+ANH4J	Atmospheric ammonia reacts to form ammonium sulfates and nitrates
Sulfates	ASO4I+ASO4J	PMS, SO _x
Nitrates	ANO3I+ANO3J	NO _x
Elemental Carbon	AECI+AECJ	PMNV
Organic Carbon	Primary: AORGAI+AORGAIB+AORGBI+AORGBJ	PMFO
	Secondary: 1.167*(AORGP AI+AORGP AJ)	
Crustal Material	A25I+A25J	Not Caused By Aircraft

The ambient particulate matter concentrations without aircraft are shown below in Figure 26. The area modeled was a 126km by 120km rectangle including all of the Atlanta metro area and surrounding region. The plot shows that the highest ambient concentrations of PM, those shown in red, were located in the Atlanta metro area.

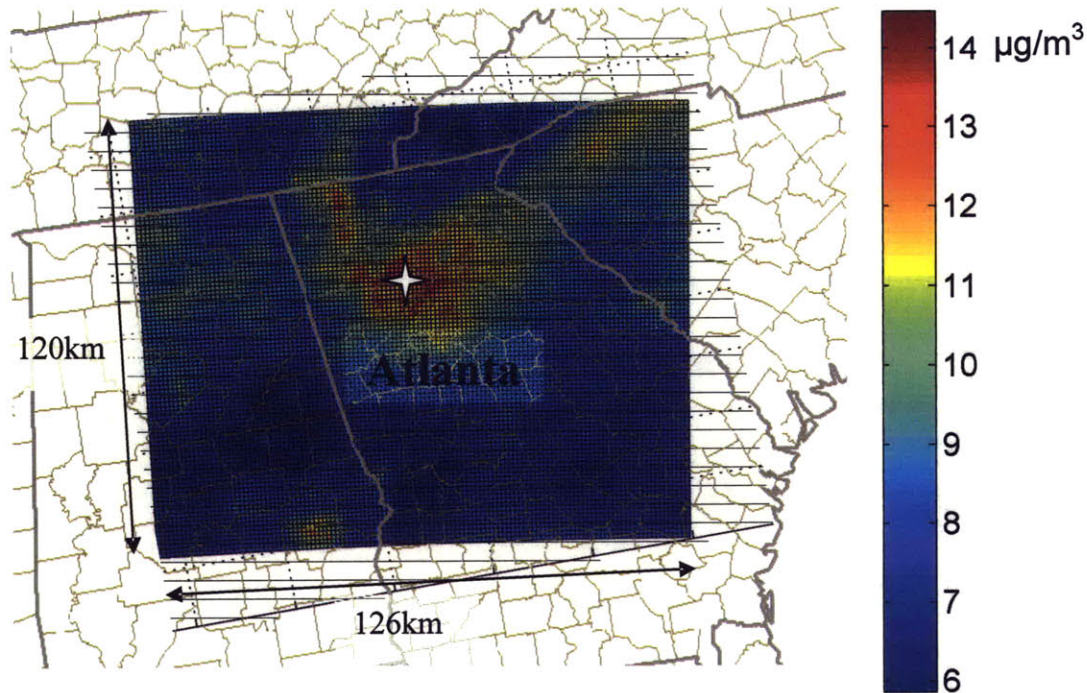


Figure 26 Ambient Concentrations of PM_{2.5} in the Study Area

The incremental contribution of aircraft emissions to the ambient particulate matter concentration for each of the fuel scenarios is shown in Figure 28. The incremental contribution is the difference between the individual fuel case and the ambient case. Crustal particulate matter was not shown due to its independence from aircraft emissions. In order to provide insight into the spatial reach of the aircraft contribution to ambient particulate matter concentrations, the results are shown as averages according to distance. These distances were approximately radial, as shown below in Figure 27.

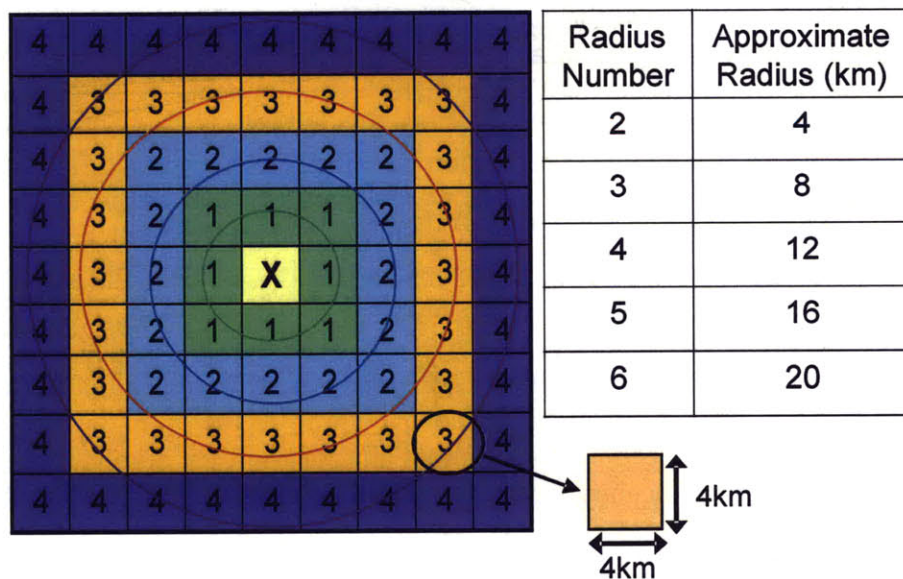


Figure 27 Radial Distance Approximation Used for Figures 28 and 29

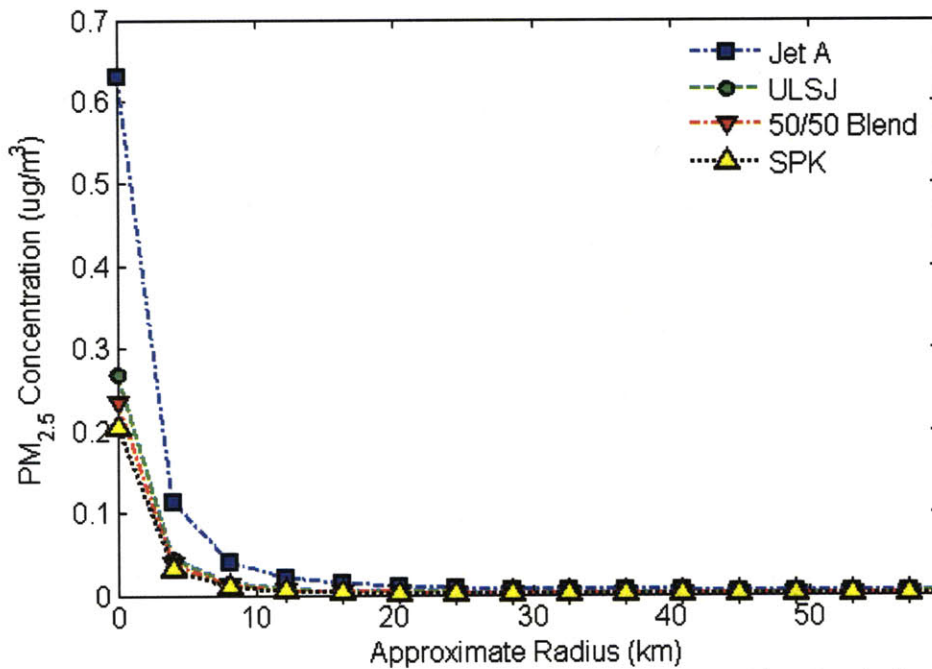


Figure 28 Incremental Contributions of Aircraft Emissions to Ambient Particulate Matter Concentrations for Each of the Alternative Fuel Scenarios Considered.

As seen in Figure 28 and as would be expected from the inventory scaling, the Jet A scenario produced the highest incremental ambient particulate matter concentrations followed by ULSJ, the 50/50 blend and then SPK. In the grid cell with the highest concentration, the incremental contribution from Jet A was $0.64 \mu\text{g}/\text{m}^3$. For comparison, the ambient concentration from all sources was $10.3 \mu\text{g}/\text{m}^3$; the incremental ambient particulate matter contribution from aircraft in the Jet A case was approximately 6% of this.

The change in the composition of the aircraft contribution to ambient particulate matter concentrations are shown in Figure 29 as for the four fuel scenarios examined with CMAQ. Each plot is a stacked line plot of the different components' contribution. In the Jet A scenario, the largest aircraft contribution was due to sulfates. In the three alternative fuel scenarios, however, the sulfate contribution was negligible. This was expected as both the SO_x and PMS emissions inventories were reduced by 98% as discussed in 7.3. In the alternative fuel scenarios, the highest contribution to ambient particulate matter concentrations was organics followed by the contribution from elemental carbon. The elemental carbon contribution changed across alternative fuel scenarios. It was highest in the ULSJ scenario where elemental carbon emissions were unchanged relative to conventional jet fuel followed by the 50/50 blend where the elemental carbon emissions were reduced by 42%. The elemental carbon contribution was lowest in the SPK case where its emissions were reduced by 76%. Across all scenarios, the nitrate contribution to ambient particulate matter concentrations was negligible, which is consistent with prior analysis of ATL (Arunachalam et al. 2008); however, this does contradict other sources in the literature which suggest that nitrates may be the largest source of aircraft related PM, for example (Brunelle-Yeung 2009). This difference is likely due to the variations in

atmospheric chemistry across various regions of the United States, and it should be examined as part of additional research.

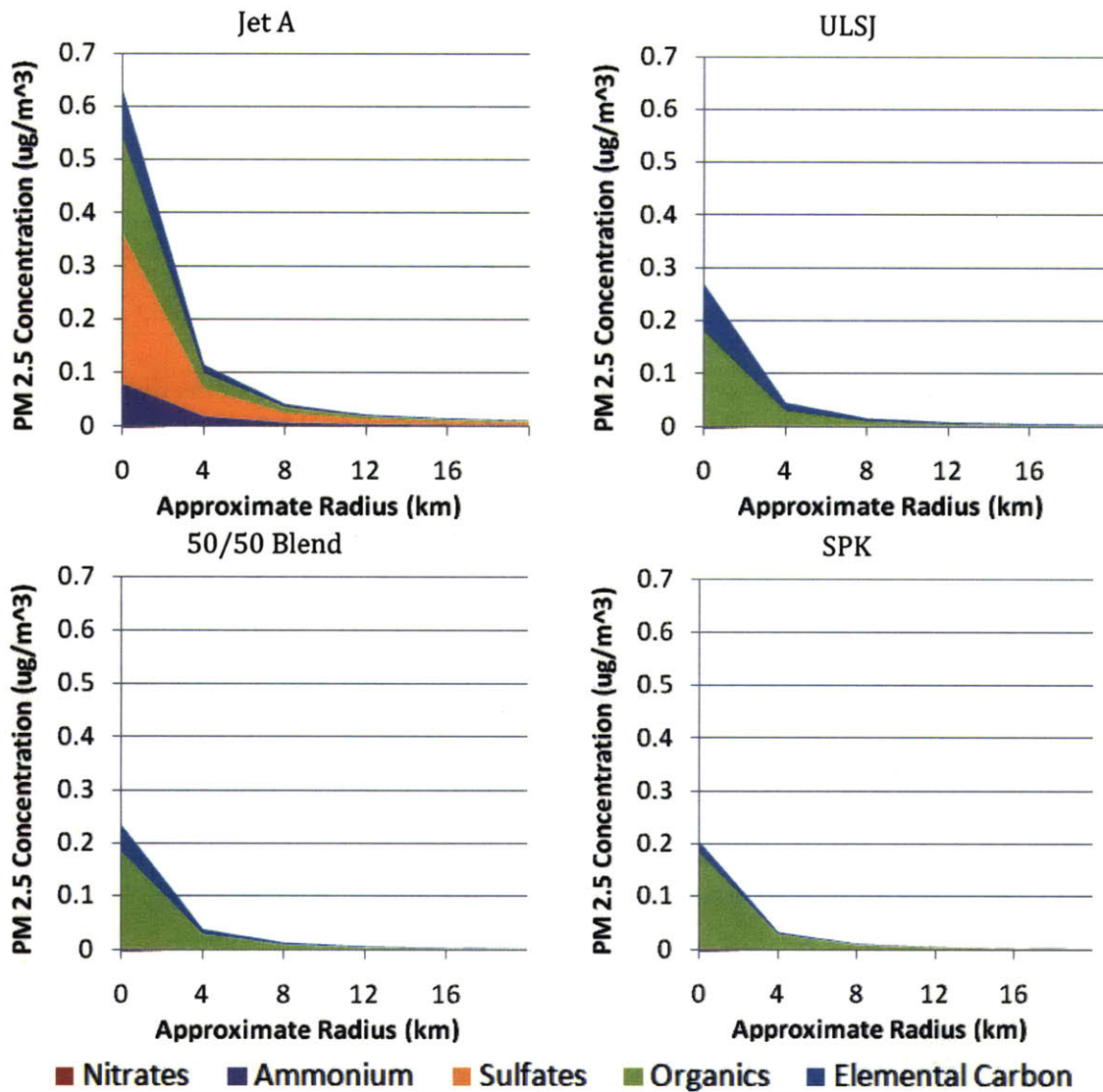


Figure 29 Stacked Aircraft Ambient Particulate Matter Concentrations by Radius by Species

7.5 MATS Emission Concentration Results

As discussed in section 6.4, the MATS software was used to adjust the ambient particulate matter levels to reflect monitor data and to apply the EPA SANDWICH method in order to add water to the total ambient particulate matter mass. Hydrating the ambient particulate matter concentration increases the mass of both the ambient particulate matter as well as that caused by aircraft emissions. This step was needed because epidemiological studies and regulations are based on hydrated PM_{2.5} measured using the Federal Reference Method, which uses partially hydrated PM.

The relative ambient concentrations for the dry (ionic) and hydrated PM_{2.5} are shown in Table 30. Hydrating increased the ambient PM_{2.5} concentration resulting from Jet A by

approximately a factor of 2 while it increased the ambient PM_{2.5} concentration from ULSJ by approximately a factor of 2.5 and a factor 3 for both the 50/50 blend and SPK. The hydration also increased the PM_{2.5} concentration difference between Jet A and the alternative fuels. For example, without hydration the reduction in PM_{2.5} concentrations from Jet A to ULSJ was 0.36 µg/m³; when the PM_{2.5} was hydrated, that increased to a reduction of 0.61 µg/m³. The percent reduction also changed.

Table 30 Comparison of Ambient PM_{2.5} Concentration due to Aircraft in the Maximum Concentration Grid Cell for both Dry and Hydrated PM_{2.5}

Fuel	Jet A	ULSJ	50/50 Blend	SPK
Dry PM _{2.5} (µg/m ³)	0.63	0.27	0.23	0.21
Hydrated PM _{2.5} (µg/m ³)	1.30	0.69	0.66	0.62

The relative changes in PM_{2.5} concentration with hydration were due to the differences in the chemical make-up of the PM_{2.5} emissions. The compositional breakouts for the maximum aircraft PM_{2.5} concentration grid cell are shown on a percent basis in Figure 30. Column one of Figure 30 shows the composition of the CMAQ output, column two shows the output of the MATS program with the mass from the water as a separate species and column three shows the MATS output with the water and ammonium masses apportioned to the species, as discussed in 6.4. The difference in relative contributions from the species when compared with the CMAQ output in Figure 29 is due to the MATS process of adjusting modeled data to more closely reflect area measurement data (Abt Associates 2009). The differences in percentage compositions between wet and dry aircraft PM_{2.5} calculated by MATS are due to the SANDWICH method. In the SANDWICH method, PM_{2.5} from sulfates and nitrates are hydrated and the ammonium is apportioned to ammonium sulfates and ammonium nitrates as discussed in 6.4. This is why in column three of Figure 30 there is no direct reference to ammonium or particle bound water. The third column for each fuel in Figure 30 is also more correctly interpreted as contributions from ammonium sulfates and ammonium nitrates rather than simply sulfates, nitrates, and ammonium.

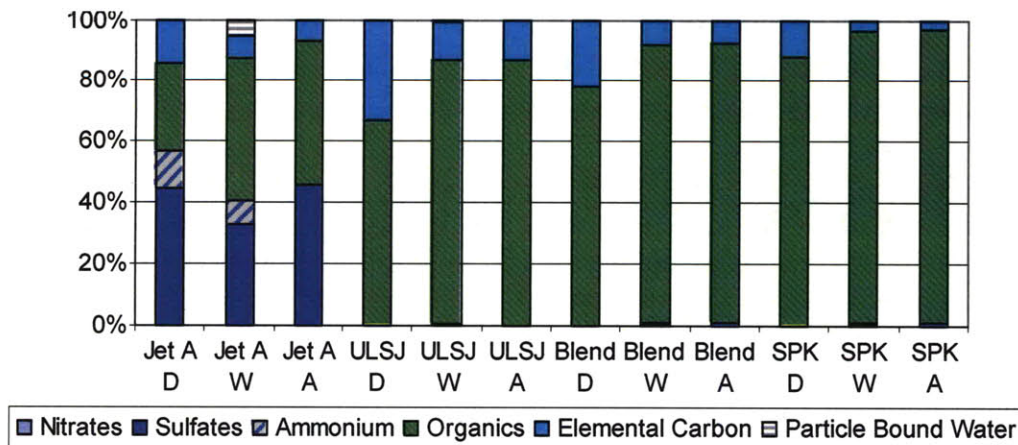


Figure 30 Composition of Aircraft PM_{2.5} in the Maximum Concentration Grid Cell Dry (D), Hydrated or Wet (W), and with Water Apportionment (A)

Chapter 8 Conclusions on the Relative Impacts of Fuel Composition on PM_{2.5} from GSE and Aircraft

This thesis has quantified the potential benefits of alternative jet fuel use at a particular airport. These benefits were quantified through the creation of a first-order general scaling methodology, emissions inventory analysis of the Atlanta Hartsfield-Jackson International Airport and full air quality modeling of the area surrounding the Atlanta Hartsfield-Jackson International Airport.

First, this thesis presented a first-order general methodology for scaling both aircraft and GSE air quality pollutants (primary particulate matter, NO_x, SO_x, HC and CO) for SPK and ULSJ fuel use. Due to its effect on health impacts, those species that contribute to ambient particulate matter concentrations were the primary focus (for this work, fine particulate matter was the focus, PM_{2.5}). This method scales GSE emissions according to published experimental results using Fischer Tropsch diesel fuels and JP-8 and the analysis indicated a potential 52% reduction in primary particulate matter emissions from GSE from the use of ULSJ or SPK fuels.

Aircraft emissions were scaled with published experimental results from SPK emission tests. Primary particulate matter emissions were examined with the FOA3a method. The analysis indicated a potential 98% decrease in primary particulate matter emissions due to sulfur (PMS) and SO_x emissions for both SPK and ULSJ fuel use and an additional 76% decrease in primary particulate matter emissions due to elemental carbon (PM_{NV}) for SPK fuel use. There may be additional reductions in NO_x emissions; however, published preliminary experimental results are currently within experimental uncertainty.

Inventory analysis and a regional air quality simulation of the Atlanta Hartsfield-Jackson International Airport were completed to understand the effects of the emission changes on ambient particulate matter concentrations. Full year emission inventories were created using EDMS with the months of June and July analyzed for ambient air quality using CMAQ. According to the emission analysis, 11% of airport primary particulate matter emissions were due to GSE in the base case where Jet A was used in aircraft and ULSD was used in diesel GSE (see Figure 31). Due to uncertainty with regard to the amount of fuel burned for GSE, this percentage may be as low as 2%. In the base case, GSE also produced less than 10% of SO_x and NO_x, both of which are secondary PM precursors. Because the GSE emissions were both marginal and not well defined, the air quality analyses considered only aircraft emissions.

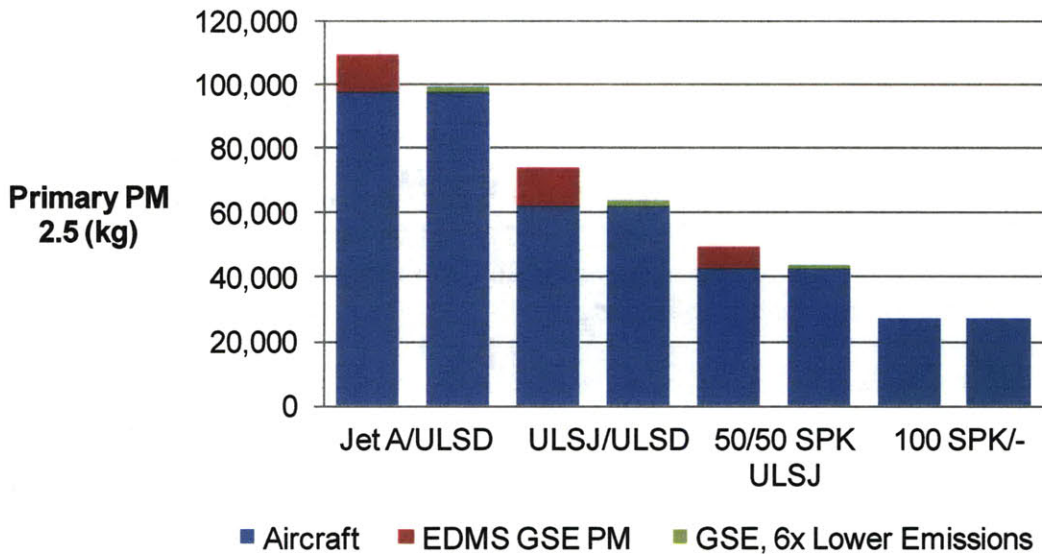


Figure 31 Scaled Primary Particulate Matter Emissions Inventories for GSE and Aircraft

The CMAQ regional air quality analysis of the Atlanta Hartsfield-Jackson International Airport indicated that alternative jet fuels have the potential to reduce air quality impacts. In the base case with aircraft using Jet A, aircraft contribute a maximum of $0.64 \mu\text{g}/\text{m}^3$ to ambient particulate matter concentrations; this includes both the primary and secondary contributions (see Figure 32); this was about 6% of the total ambient particulate matter concentration. The model indicated that implementing ULSJ at the airport could reduce the aircraft contribution to ambient particulate matter concentrations in the most affected area modeled by a factor of 2.3 and the use of an SPK fuel could reduce the total aircraft contribution to ambient particulate matter concentration by a factor of 3.0. Thus, although there are benefits in switching to an SPK fuel, including the potential to produce fuels with lower environmental footprints, the majority of the benefit at Atlanta from using an alternative jet fuel in aircraft was captured by lowering the sulfur content of the fuel. The CMAQ analysis also indicated that the concentration of air quality pollutants due to aircraft became less than $0.01 \mu\text{g}/\text{m}^3$ after a distance of approximately 20km.

The EPA MATS program was used to translate the CMAQ ionic (dry) $\text{PM}_{2.5}$ concentrations to mass concentrations with hydration levels consistent with the federal reference method. MATS uses monitor data and chemistry models to adjust model data to observed data and calculated particle bound water. Results from the MATS analysis showed that hydrating the $\text{PM}_{2.5}$ reduced the relative gain from switching to an alternative fuel (factor of decrease of 1.9 for ULSJ and 2.1 for SPK), but increases the absolute reductions possible ($0.61 \mu\text{g}/\text{m}^3$ for ULSJ and $0.68 \mu\text{g}/\text{m}^3$ for SPK). Additionally, the MATS analysis indicated that the potential percentage reduction resulting from switching from ULSJ to SPK is reduced when considering hydrated $\text{PM}_{2.5}$. CMAQ results indicated a 22% reduction while MATS results indicated a 10% reduction.

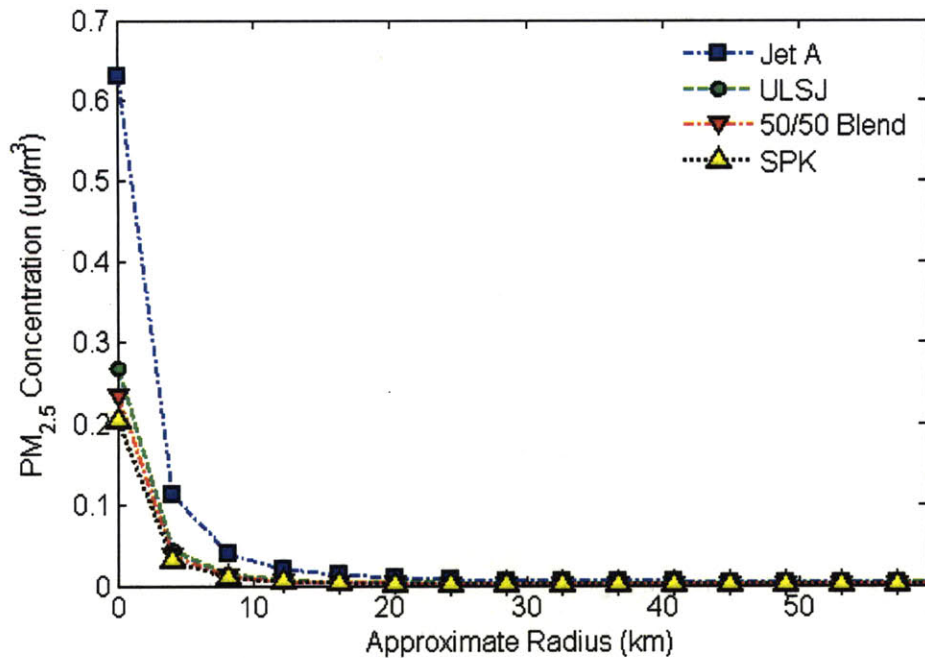


Figure 32 Incremental Contribution of Aircraft to Ambient PM Levels Calculated Using CMAQ

Table 31 Comparison of CMAQ (Dry) and MATS (Hydrated) Results

Fuel	Jet A	ULSJ	50/50 Blend	SPK
Dry PM ($\mu\text{g}/\text{m}^3$)	0.63	0.27	0.23	0.21
Hydrated PM ($\mu\text{g}/\text{m}^3$)	1.30	0.69	0.66	0.62

Through the development of emission scaling factors and the use of air quality modeling, this thesis indicates that alternative jet fuels may produce substantial decreases in air quality pollution from aircraft. In the Atlanta region, the majority of the benefit derived from the use of alternative jet fuels is due to their low sulfur content. Additional benefit of a smaller magnitude is derived from reducing elemental carbon emissions for SPK fuels. Thus although the development of SPK fuels may lessen the environmental impact of aircraft through improved fuel production processes with, for example, lower greenhouse gas emissions, significant gains in reducing aviation's impact on air quality could be made by switching to an ULS jet fuel which would rely on currently available fuel desulfurization technology. A detailed examination of the costs and benefits of such a change are currently being examined within PARTNER (Partnership for Air Transportation Noise and Emissions Reduction 2009).

Chapter 9 Future Work

The work presented in this thesis included a first-order model for scaling GSE and aircraft emissions using alternative fuels. The scaling factors presented use preliminary aircraft testing data that was available to the author during the compilation of this thesis. During the course of compiling this thesis, the author became aware of two areas of future research that are needed to improve the quality of the presented results. The first section of future work will focus on the refinement of scaling factors. The second section of future work will focus on improving the accuracy of GSE equipment inventory and emission calculations.

9.1 Refining Scaling Factors

The aircraft scaling factors presented in this work are based on preliminary data sets. The datasets for PMNV display wide error bands and show significant variation between engine settings. As shown in the CFM 56 data (Figure 16), the error bands are most significant in the lower engine settings, which are most highly weighted. The PMNV data sets, which are currently available, also only represent two jet engines. In order to scale a variety of aircraft engines, either a single factor based on testing of a representative sample of aircraft engines or multiple scaling factors tailored to engine types should be developed. At the time of writing, the datasets for both NO_x and UHC with alternative jet fuels were not developed. Scaling factors as discussed for PMNV should be developed as data becomes available. At minimum for all scaling factors, additional data should be integrated into the current scaling factor as it becomes available. As a first step, the results of the recent AAFEX tests on the CFM56 engine should be incorporated into the scaling relationships that were presented here perhaps even replacing them.

Mirroring the aircraft, the datasets for jet fuels in GSE are not well developed. As discussed in Chapter 4, there was variation both in testing methodology and fuel properties, which produce difficulty in comparing results. The test results available for SPK fuels are predominantly Fischer Tropsch diesel fuels and preliminary results indicate that non-negligible differences between these fuels and Fischer Tropsch jet fuels. Well controlled testing across realistic GSE operation test cycles using jet fuels should be conducted to allow for the development of appropriate GSE scaling factors.

9.2 Accuracy of Ground Support Equipment Models

There are a variety of uncertainties, which could be improved throughout the calculation of GSE emissions in both the base NONROAD model and the EDMS implementation. The NONROAD model was not developed specifically for GSE. As a result, the derivation of emission factors for the NONROAD model for airport GSE includes no testing of ground support equipment. All ground support equipment is assigned to the same category, regardless of type. These share load factors (LFs) and transient adjustment factors (TAFs). Again, an LF indicates the fraction of the total engine capacity used and a TAF indicates a fuel burn adjustment for real usage versus steady state. All equipment in the NONROAD model is assigned one of two LFs, high or low. All GSE are assigned the high LF which is based on the average load factor of an

agricultural tractor , a crawler dozer, a rubber-tire loader and an excavator (Environmental Protection Agency 2004). Thus, a fuel truck and an aircraft tow tractor are modeled as the same. The TAF for all GSE is based on testing of a large construction loader; the assumption of equivalency in transient emission adjustment between a construction loader and a fuel truck increases the emissions by up to 47% from steady state. Again, these assumptions were made in the NONROAD model due to a paucity of non-road engine data and no data specifically from or about GSE. Improving these assumptions through emissions testing of GSE with ultra low sulfur and alternative fuels either in the field or using a test cycle designed to mimic drive cycles of GSE would advance the state of knowledge and clarify these uncertainties.

Within EDMS, the selection of vehicle types and the number of vehicles show discrepancies when compared to the actual ATL GSE inventory. As discussed in 6.2, neither the gross number of vehicles nor types of vehicles (function or fuel) estimated by EDMS match. In order to confirm that EDMS computes the correct number and usage of GSE, GSE inventories and studies of their usage should be undertaken at multiple airport sizes. The results should be fed back into an improved version of EDMS.

Works Cited

- Abt Associates (2009). Modeled Attainment Test Software User's Manual, Environmental Protection Agency.
- ACOM-TARDEC (2001). JP-8 Single Fuel Forward, Information Compendium. U. S. A. ACOM-TARDEC.
- Airports Council International. (2009). "Annual Traffic Reports." Retrieved April 07, 2009, from http://www.airports.org/cda/aci_common/display/main/aci_content07_c.jsp?zn=aci&cp=1-5_666_2_.
- Alleman, T. L. and R. L. McCormick (2003). "Fischer-Tropsch diesel fuels - properties and exhaust emissions: a literature review." SAE Technical Paper Series 2003-01-0763.
- Anderson, B. (2009). Overview and Highlights of the Alternative Aviation Fuel Experiment. American Association for Aerosol Research 2009 Conference.
- Arunachalam, S., B. H. Baek, B. Wang, N. Davis, A. Holland, Z. Adelman, U. Shankar, F. Binkowski, A. Hanna, T. Thrasher and P. Soucaos. (2008). 13th Conference on Aviation, Range and Aerospace Meteorology, New Orleans.
- Bowden, J. N. and S. R. Westbrook (1989). "Jet Kerosene Fuels for Military Diesel Application." SAE Technical Paper Series 892070.
- Brunelle-Yeung, E. (2009). The Impacts of Aviation Emissions on Human Health through Changes in Air Quality and UV Irradiance. Aeronautics and Astronautics. Cambridge, Massachusetts Institute of Technology. **Master of Science**.
- Byud, D. and K. L. Schere (2006). "Review of the Governing Equations, Computational Algorithms and Components of the Models-3 Community Multiscale Air Quality (CMAQ) Modeling System." Applied Mechanics Review 59: 51-77.
- Cheng, A. S. and R. W. Dibble (1999). "Emissions Performance of Oxygenate-in-Diesel Blends and Fischer-Tropsch Diesel in a Compression Ignition Engine." SAE Technical Paper Series 1999-01-3606.
- Chevron. (2006). "Aviation Fuels Technical Review." from http://www.chevronglobalaviation.com/docs/aviation_tech_review.pdf.
- Chevron (2007). "Diesel Fuels Technical Review." Available from http://www.algae-x.net/_technicalinfo/techinf_2.pdf
- Clark, N. N., C. M. Atkinson, G. Thompson, and R. Nine. (1999). "Transient Emissions Comparisons of Alternative Compression Ignition Fuels." SAE Technical Paper Series 1999-01-1117.
- Clark, N, M, Gautam, D. Lyons, C. Atkinson, W. Xie, P. Norton. K. Vertin. S. Gouguen and J. Eberhardt. (1999). "On-Road Use of Fischer-Tropsch Diesel Blends." SAE Technical Paper Series 1999-01-2251.
- CMAS. (2008). "SMOKE v2.5 User's Manual." Retrieved April 7, 2009, from <http://www.smoke-model.org/version2.5/index.cfm>.
- Commercial Aviation Alternative Fuels Initiative (2009). Landmark synthetic jet fuel specification passes critical hurdle. Available from <http://www.caafi.org/files/altfuelstandard-rls6-09.pdf>
- Coordinating Research Council (2009). Survey of Sulfur Levels in Commercial Jet Fuel.

- Corporan, E., M. J. DeWitt, et al. (2007). DoD Assured Fuels Initiative: B-52 Aircraft Emissions Burning a Fischer-Tropsch/JP-8 Fuel Blend. 10th International Conference on Stability, Handling and Use of Liquid Fuels, Tucson, Arizona.
- Defense Energy Support Center (2006). 2006 Petroleum Quality Information System Report.
- Defense Energy Support Center (2008). 2008 Petroleum Quality Information System Fuels Data.
- Defense Standard 91-91 (2008). Turbine Fuel, Aviation Kerosene Type, Jet A-1 NATO Code: F-35 Joint Service Designation: AVTUR, UK Ministry of Defense.
- DeWitt, M. J. and E. Corporan (2009). AFRL Research on Engine Emissions Characterization of Alternative Fuels. Aviation Emissions Characterization Roadmap 7th Annual Meeting.
- DeWitt, M. J., E. Corporan, J. Graham and D. Minus (2008). "Effects of Aromatic Type and Concentration in Fischer-Tropsch Fuel on Emissions Production and Material Compatibility." Energy & Fuels **22**: 2411-2418.
- Edwards, T. (2008). Cetane Numbers of Synthetic Jet Fuel. Personal Communication with P. Donohoo. Cambridge.
- Environmental Protection Agency (2008). "Photochemical Modeling Tools." Retrieved August 9, 2009, from http://www.epa.gov/scram001/modelingapps_mats.htm.
- Environmental Protection Agency. (2008). "Greenbook." January 28, 2009, from <http://www.epa.gov/oar/oaqps/greenbk/qindex.html>.
- Environmental Protection Agency. (2009). "Basic Information on Particulate Matter." Retrieved July 28, 2009, 2009, from <http://www.epa.gov/air/particlepollution/basic.html>.
- Environmental Protection Agency. (April 27, 2004). "Diesel Fuel Sulfur Inputs for the Draft NONROAD2004 Model." Retrieved January 30, 2009, from <http://www.epa.gov/OMS/models/nonrdmdl/nonrdmdl2004/sulfur.txt>.
- Environmental Protection Agency (April, 2004). "Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling --Compression-Ignition NR-009c."
- Fanick, E. R., P. F. Schubert, (2001). "Comparison of Emission Characteristics of Conventional, Hydrotreated, and Fischer-Tropsch Diesel Fuels in a Heavy-Duty Diesel Engine." SAE Technical Paper Series **2001-01-3519**.
- Federal Aviation Administration. (2009). "Emissions and Dispersion Modeling System (EDMS)." from http://www.faa.gov/about/office_org/headquarters_offices/aep/models/edms_model/.
- Fernandes, G., J. Fuschetto, Z. Filipi, D. Assanis and H. McKee (2007). "Impact of Military JP-8 Fuel on Heavy-Duty Diesel Engine Performance and Emissions." Journal of Automobile Engineering **221**(Part D).
- Frame, E. A., R. A. Alvera, M.G. Blanks, R.L. Freerks, L.L. Stavinoha, P. A. Muzzell, and L. Villahermosa (2004). "Assessment of fischer-tropsch fuel for military use in a 6.5L diesel engine." SAE Transactions **113**(4).
- Gross, S. (2007). UOP to Deliver Biofuel Technology for Military Jets. UOP Press Release. Des Plaines.
- Harley, S. (2002) "BP Leads Oil Industry with the Launch of Pioneering Sulphur-Free Fuels." from <http://www.chemie.de/news/e/8571/>

- Hartsfield-Jackson Atlanta International Airport. (2008). Year-To-Date Airport Traffic Report, December 2007.
- Hileman, J. I., R.W. Stratton and P. E. Donohoo (2010). "Energy Content and Alternative Jet Fuel Viability." Journal of Propulsion and Power **Forthcoming**.
- Hileman, J. I., D. Ortiz, J. Bartis, H.M. Wong, P. Donohoo, M. Weiss and I. Waitz (2009). "Near-Term Feasibility of Alternative Jet Fuels." PARTNER and Rand Corporation Report.
<http://web.mit.edu/aeroastro/partner/reports/proj17/altfuelfeasrpt.pdf>
- ICAO (2008). ICAO Engine Exhaust Emissions Data Bank.
- ICAO (1993). "International Standards and Recommended Practices: Environmental Protection, Annex 16." **2**.
- Johnson, J. W., P. J. Berlowitz, R.J. Wittenbring, W.B. Genetti, L.L. Ansell, Y. Kwon, and D.J. Rickeard(2001). "Emissions from Fischer-Tropsch Diesel Fuels." SAE Technical Paper Series.
- Kidoguchi, Y., C. Yang, and K. Miwea (2000). "Effects of Fuel Properties on Combustion and Emission Characteristics of a Direct-Injection Diesel Engine." SAE Technical Paper Series.
- Lee, R., J. Pedley, and C. Hobbs (1998). Fuel Quality Impact on Heavy Duty Diesel Emissions: -A Literature Review. International Fall Fuels and Lubricants Meeting and Exposition, San Francisco, California, SAE.
- Marker, T. L., P. Kokayeff, et al. (2007). Green Diesel production from Vegetable Oil. AICHE, UOP.
- Miake-Lye, R. and M. Timko (2008). Personal Communication with P. Donohoo. Cambridge, Massachusetts.
- Mobile, E. (undated) "Diesel FAQ."
- Moses, C. A., T. B. Biddle, S.P. Seto, C. Lewis, R.C. Williams and P. Roets (2007). Combustion and Operational Characteristics of Sasol CTL Fully Synthetic Jet Fuel. IASH 2007, The 10th International Conference on Stability, Handling and Use of Liquid Fuels. Tucson, Arizona.
- Moses, C. A., G. Wilson, and P. Roets (2003). "Evaluation of Synthetic Kerosene for Suitability as Jet Fuel."
- NATO Code F-35 (2007)Evaluation of Synthetic Kerosene for Suitability as Jet Fuel. United Kingdom.
- Ng, H., R. Carlson, and M. Wang (2008). "Comparing the Performance of GTL/ULSD Blends in Older and Newer Diesel Passenger Cars." SAE Technical Paper Series.
- Nord, K. and D. Haupt (2002). "Evaluating a Fischer-Tropsch Fuel, Eco-Par, in a Valment Diesel Engine." SAE Technical Paper Series 2002-01-2726.
- Partnership for AiR Transportation Noise and Emissions Reduction. (2009). "Project 27: Environmental Cost-Benefit Analysis of Ultra Low Sulfur Jet Fuels." Retrieved July 28, 2009, from <http://web.mit.edu/aeroastro/partner/projects/project27.html>
- Ratliff, G. (2007). Preliminary Assessment of the Impact of Commercial Aircraft on Local Air Quality in the U.S. Engineering Systems Division. Cambridge, MIT. **Master of Science**.
- Ratliff, G., C. Sequeira, I. Waitz, M. Ohsfeldt, T. Thrasher, M. Graham and T. Thompson (2009). Aircraft Impacts on Local and Regional Air Quality in the United States. <http://web.mit.edu/aeroastro/partner/reports/proj15/proj15finalreport.pdf>

- Rojo, J. (2007). Future Trends in Local Air Quality Impacts of Aviation. Aeronautics and Astronautics. Cambridge, Massachusetts Institute of Technology. **Master of Science**.
- Rumizen, M. (2009). CAAFI Certification Progress. CAAFI R&D Team Workshop, Dayton, Ohio.
- Schaberg, P. W., I. S. Myburgh, J. J. Botha and I. A. Khalek (2000). "Comparative Emissions Performance of Sasol Fischer-Tropsch Diesel Fuel in Current and Older Technology Heavy-Duty Engines." SAE Technical Paper Series 2000-01-1912.
- Schaberg, P. W., I. S. Myburgh, J.J. Botha, P.N. Roets and C.L. Viljoen (1997). "Diesel Exhaust Emissions Using Sasol Slurry Phase Distillate Process Fuels." SAE Technical Paper Series 972898.
- Sequeira, C. (2008). Relationships Between Emissions-Related Aviation Regulations and Human Health. Cambridge, Massachusetts Institute of Technology. **Master of Science**
- Sirman, M. B., E. C. Owens and K.A. Whitney (2000). "Emissions Comparison of Alternative Fuels in an Advanced Automotive Diesel Engine." SAE Technical Paper Series 2000-01-2048.
- Smith, R. and Environmental Protection Agency (2009). EPA Fuels Testing Data. Personal Communication to D. Ortiz and Personal Communication from D.Ortiz to J. Hileman.
- Syntroleum (2007). Syntroleum Signs Contract to Deliver Renewable Alternative jet Fuel to U.S. Department of Defense. Syntroleum Press Release.
- Tao Wu, Z. H., W.-g. Zhang, J. Fang and Q. Yin (2007). "Physical and Chemical Properties of GTL-Diesel Fuel Blends and Their Effects on Engine Performance and Emissions of a Multicylinder DI Compression Ignition Engine." Energy & Fuels 21: 1908-1914.
- Timko, M. T., A. J. Beyersdorf, A. Bhargava, E.L. Winstead, K.L. Thornhill, D.S. Liscinsky, J. Souza, C. Wey, K. Tacina, Z. Yu, B.U. Onasch, R.C. Miake-Lye, E. Corporan, M.J. DeWitt, C.D. Klingshirm and R. Howard (2008). The Impact of Alternative Fuels on Aircraft Emissions. American Association for Aerosol Research.
- U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (September) "What is Fischer Tropsch Diesel?" from http://www.afdc.energy.gov/afdc/fuels/emerging_diesel_what_is.html
- Watkiss, P., S. Pye, and M. Holland (2005). CAFE CBA: Baseline Analysis 2000 to 2020.
- Webb, S. (2008). Atlanta Delta GSE Inventory. Personal Communication with P. Donohoo.
- Whitefield, P. D. (2008). The Emissions of Alternative Aviation Fuels. 11th PARTNER Advisory Board Meeting, Chicago, Illinois.
- Whitefield, P. D., P. Lobo, R.C. Miake-Lye, C. Taylor, G. Ratliff, S. Lukachko, C. Sequeira, J. Hileman, I. Waitz, S. Webb, T. Thrasher, M. Ohsfeldt, H. Kaing and S.C. Essama (2008). Summarizing and Interpreting Aircraft Gaseous and Particulate Emissions Data. Airport Cooperative Research Program Report Number 9. Transportation Research Board.

- Yost, D. M. (1992). "Effect of JP-8 Fuel on Material-Handling Engines." Belvoir Fuels and Lubricants Research Facility (SwRI) Interim Report BFLRF No.285
- Yost, D. M., D. A. Montalvo, and E. A. Frame (1996). "U.S. Army Investigation of Diesel Exhaust Emissions Using JP-8 Fuels with Varying Sulfur Content." SAE Technical Paper Series 961981.

Appendix A Stanadyne Fuel Pumps Repair Bulletins

NO: 484R4



SERVICE BULLETIN

LIMITED
DISTRIBUTION

DATE: August 10, 1995

SUPERSEDES: S.B. 484113 dated 1/8/95
and S.L. 289 dated 8/9/94

LIMITED DISTRIBUTION — GENERAL MOTORS

SUBJECT: HOT ENGINE RESTART COMPLAINTS — GM 6.5L DB2 EQUIPPED APPLICATIONS

**MODELS AFFECTED: DB2-4911, 4927, 4970, 4971, 5079, 5088
5089, 5119, 5129, 5149 AND 5157**

There have been a number of hot engine restart complaints on GM 6.5L DB2 applications with the affected pump models, particularly in areas where ambient temperatures are high and generally following an engine shutdown period of approximately 15-30 minutes. Effective with pump serial number 7768648, Stanadyne began utilizing a new Hydraulic Head and Rotor Assembly, PIN 31506, to address this condition. The 31506 H&R contains design changes which improve the cranking efficiency with hot and/or lower viscosity diesel fuels and it supersedes the original H&R assembly, PIN 29124. It is important to note that only a small percentage of the 1992 and 1993 6.5L diesels have verifiable hot starting conditions which require the H&R change.

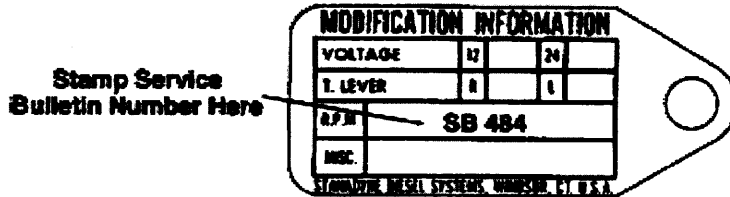
In previous issues of this bulletin Stanadyne has instructed the service network to install a replacement Head and Rotor assembly into the pumps (P/N C1506 which is the remanufactured version of P/N 31506) without testing the pumps as received to determine whether they meet minimum cranking fuel requirements. Stanadyne will now revert to normal warranty procedures where the pump must be tested as received. If the pump meets the minimum cranking delivery specifications, regardless of which H&R it contains, it must either be returned to the customer without further repairs being made or if the customer wishes, a C1506 H&R may be installed but will be chargeable to the customer (the GM Dealer performing the diagnostics and pump removal and reinstallation) - whether the pump is within the Stanadyne warranty period or not. NOTE: In Canada where a DB2 exchange program is in effect for General Motors, dealers are to issue exchange units as they normally would, but pumps which pass the test as received criteria are to be overhauled *without the addition of the C1506 H&R assembly and the claim marked "Fault Not Found"*.

As a result, a C1506 Head and Rotor may only be installed into pumps and a claim submitted to Stanadyne when the pump fails to meet the minimum

Diesel Systems Division, Stanadyne Automotive Corp.
92 Deerfield Road, Windsor, CT 06095, USA Tel: (203) 525-0821; Telex: 99218; Telecopy: (203) 525-4215

cranking delivery test and is within the 3 year/50,000 mile (80,000 km) Stanadyne warranty period.

When one of the affected pump models is upgraded with a C1506 H&R to address a hot, hard starting complaint, it must be identified by stamping "SB484" in the miscellaneous section of a 30607 Stanadyne Modification Nameplate as shown below and then affixing the plate to the pump under the rear governor cover screw as outlined in Service Bulletin 486.



Modification Nameplate 30607

Warranty

If one of the affected DB2 model injection pumps is received for a complaint of hard starting hot, and fails to meet the minimum cranking delivery specification when tested as received, and is within Stanadyne's warranty period of 3 years or 50,000 miles (whichever comes first), Service Dealers may submit a warranty claim for up to 3.7 hours labor broken down as follows:

<u>Labor Operation No.</u>	<u>Description</u>	<u>Allowance (Hours)</u>
00	Administration Time	0.5
01	Test as Received	1.0
50	Disassembly, Reassembly	1.2
51	Calibration	1.0
TOTAL:		3.7

Please circle Class Code 3 and reference S.B. 484 on your warranty claim form. Canadian Service Dealers may submit a claim for overhauling the pump for their exchange unit shelf stock as outlined in Service Letter 273C.

NOTE: Only remanufactured H&R assemblies (P/N C1506) are to be used for this repair when performed within the Stanadyne warranty period.

**Technical Support Group
Product Support Department**



SERVICE BULLETIN

Date: January 30, 1988

Supersedes: S.B. 284R1 and S.B. 284A

**SUBJECT: STANDARDIZATION OF ELASTOMER INSERT DRIVE (EID)
GOVERNOR WEIGHT RETAINER ASSEMBLIES**

As you may know, Stanadyne first introduced EID governor weight retainers in 1985 for certain automotive pump applications and recently began utilizing EID weight retainers on all tang driven DB and DB2 applications, both automotive and non-automotive.

Stanadyne has now designed and released three additional EID weight retainers for spline driven DB and DC pump applications. These spline and tang driven-type EID weight retainers supersede all previously used flex ring and welded governor weight retainer assemblies.

The following chart provides the complete list of available EID weight retainers and supersession information:

EID WEIGHT RETAINER ASSEMBLIES

Tang Drive			
Part Number	Description	Identification	Supersedes
28089	Large Heel Radius, Copper Plated	None	None
28370*	Large Heel Radius	None	18987, 22940, 23375
28681	Large Heel Radius, Nickel Plated	R	20235
29111	Sharp Heel Radius	L	19528, 23853, 23376
Spline Drive			
Part Number	Description	Identification	Supersedes
29294	Large Heel Radius	None	19537
29295	Sharp Heel Radius	L	19541, 19542
29296	Large Heel Radius, Nickel Plated	R	20228

* Supplied for service in Kit 27984 which originally contained EID weight retainer assembly 24295 (Ref. S.B. 426).

Diesel Systems Division, Stanadyne Automotive Corp.
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Identification

EID weight retainer assemblies are identified in the following manner:

- Large heel radius:** No identification mark (previously marked "CL" on weight retainers prior to the EID version).
- Sharp heel radius:** Stamped "L" on the flat surface area of the retainer between the weight sockets.
- Nickel plated:** Stamped "R" on the flat surface area of the retainer between the weight sockets.

Flexible Retaining Rings

Although the flex ring governor weight retainer assemblies have been superseded by the EID version, the 22935 flexible retaining ring is still available for servicing these governor weight assemblies. Flex ring replacement instructions are as follows:

Disassembly

To disassemble a retaining ring from a weight retainer, insert the tips of snap ring pliers 13337 under the flexible ring between any two rivets. Expand the pliers while applying pressure in an upward direction. A slight twisting motion will snap the ring off the rivet. The ring may then be pulled by hand from the remaining rivets.

Assembly

To assemble a new flex ring to a weight retainer:

1. Place the weight retainer cage with the three rivets face up on a work bench.
2. Assemble the hub (rivets facing up) to the weight cage.
3. Insert the tips of snap ring pliers 13337 into one of the holes in the new flexible retaining ring, and expand the hole by squeezing the pliers. *Caution: over expansion may damage the ring.*
4. While holding the hub and retainer with one hand, catch the back edge of the hole in the ring under the head of a rivet on the retainer (Figure 1).
5. Pivot the pliers around the rivet until the ring snaps into its groove beneath the head of the rivet.
6. Repeat this process to assemble the ring to the remaining five rivets.

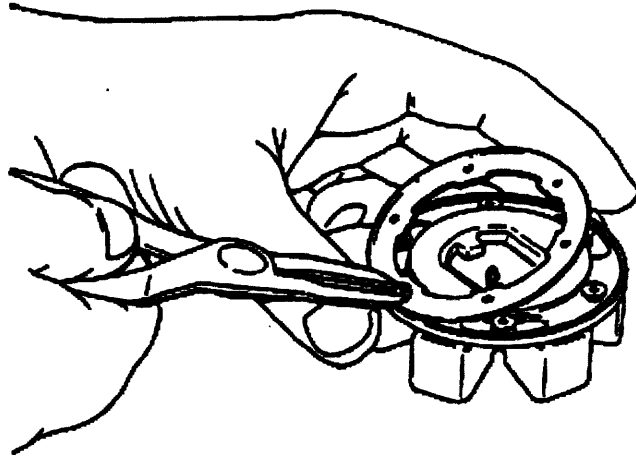


Figure 1

Governor Weight Retainers & Thrust Washers

Weight retainers utilized prior to the EID standardization, were identified by a stamped "L" (sharp corner) or "CL" (radiused corner) in the location as shown in Figure 2. In 1981 the inside diameter of the weight retainer was increased (Ref. Figure 3) to allow for the use of a thrust washer without a chamfered edge and were identified by a stamped line under the "L" or "CL".

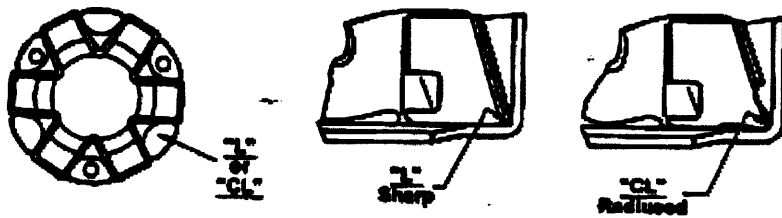


Figure 2

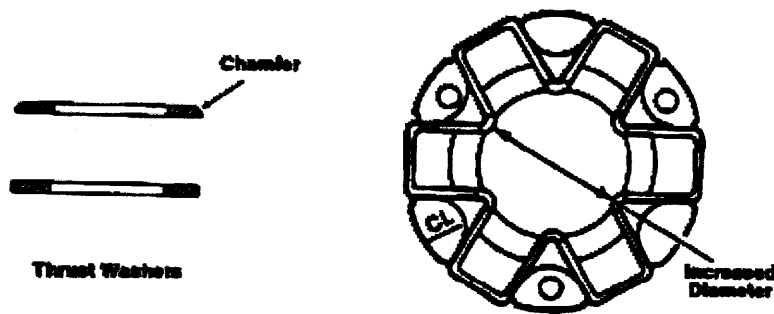


Figure 3

A chamfered thrust washer must be used in conjunction with weight retainers with the smaller inside diameter. This chamfer eliminates the possibility of interference between the thrust washer and the weight sockets when the weights are in their outermost position. *NOTE: A new plated, chamfered thrust washer, part number 29709, is now available for pumps which are equipped with a small inside diameter weight retainers that operate on lower viscosity fuels (Ref. S.B. 125).*

Un-chamfered thrust washers should be utilized on pumps with increased inside diameter (which includes all EID types) weight retainer assemblies. However, the chamfered thrust washers may be used with all weight retainer assemblies. Thrust washer part numbers and usage is provided in the following chart:

<u>Part No.</u>	<u>Description</u>	<u>Where Used</u>
11620	Chamfered	Smaller inside diameter Weight Retainers (prior to 1981)
29709	Chamfered (Plated)	
20222	Un-chamfered (Plated)	Increased inside diameter Weight Retainers (1981 - present, all EID's)
23272	Un-chamfered	

**Technical Support Group
Product Support Department**



SERVICE BULLETIN

DATE: January 8, 1998

SUPERSEDES: S.B. 125R3 dated 6/1/93

SUBJECT: FIELD CONVERSIONS FOR LOW VISCOSITY FUEL OPERATION

Stanadyne has compiled the following information for our service network to allow for field conversions of Stanadyne fuel injection pumps for operation with fuels having a lower kinematic viscosity than DF-2.

Stanadyne recommends the use of special transfer pump and drive components to reduce wear and extend the life of the pump when operated with low viscosity fuels. Specially plated governor components, in addition to the transfer pump and drive components, are normally only recommended for applications which are equipped with speed droop governors when operating with these fuels.

Stanadyne has established the following fuel guidelines for operation of our fuel injection pumps with standard and low viscosity components. Whenever a pump is converted for low viscosity fuel operation, it is imperative that the end user understands that the low viscosity fuel components were developed for operation with fuels listed within the recommended and acceptable categories. Fuels listed within the emergency category, such as JP-4, should be used as such, on an emergency basis only.

	FUEL USAGE WITH STANDARD COMPONENTS	FUEL USAGE WITH LOW VISCOSITY COMPONENTS
Recommended	DF-2, No. 2-D	DF-2, No. 2-D, DF-1, No. 1-D
Acceptable	DF-1*, No. 1-D*, No. 4-D	JET A, JET A-1, DF-A JP-5, JP-7, JP-8
Emergency Only:	JET-A, JET A-1, DF-A, JP-4, JP-5, JP-7, JP-8, TS	JP-4, TS

* Diesel fuel grade #1 is only acceptable for use with standard components when ambient temperatures are below 32°F (0°C).

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NOTE: Home heating oils commonly carry the same No. 1 and No. 2 grade designations as Diesel fuel and often are used interchangeably with those grades of Diesel. Some home heating oils, however, do not contain the necessary additives to provide proper engine operation. It is also illegal in many countries to utilize these oils for over-the-road use when their cost does not include applicable road taxes.

The chart of components which follows will assist in determining which part changes are required to implement these field conversions. Refer to the individual pump specification to identify which standard components have a low viscosity fuel replacement.

**LOW VISCOSITY FUEL CAPABILITY
CONVERSION PARTS**

REMOVE	INSTALL	DESCRIPTION	MODEL TYPE			
			DB	DB2	DB4	DM
20511	20803	Transfer Pump Blades	X	X	X	X
20512 (O' size)	20804	Transfer Pump Blades	X	X	X	X
16753	18958	Transfer Pump Liner	X			
21232	22988	Transfer Pump Liner		X	X	X
11620	29709	Governor Thrust Washer	X	X		
23272	20222	Governor Thrust Washer		X		X
19860	23859	Governor Thrust Washer			X	
21522	24691	Drive Shaft Thrust Washer		X		
26468	26358	Drive Shaft Thrust Washer			X	
26469	26361	Shaft Retaining Ring			X	
10213	29138	Drive Shaft	X	X		
21519	28573	Drive Shaft		X		
23364	24108	Drive Shaft		X		
23452	26110	Drive Shaft		X		
26179	26238	Drive Shaft		X		
26386, 24623	26538	Drive Shaft (Ref. S.B. 419)		X		
28825	23820	Drive Shaft		X		
29783	27639	Drive Shaft		X		
30941	30940	Drive Shaft		X		
30500	31325	Drive Shaft		X		
19870	33817	Rotor Retainer (Note 1)		X		
32859	33818	Rotor Retainer (Note 1)		X		

NOTE 1: P/N's 33817 and 33818 can be used only in pump models with Pressure Compensating Transfer Pumps – Ref. S.B. 444A. These rotor retainers have a notch on the outside diameter to distinguish them from P/N's 19870 and 32859.

**ADDITIONAL PARTS FOR APPLICATIONS
EQUIPPED WITH SPEED DROOP GOVERNORS**

REMOVE	INSTALL	DESCRIPTION	MODEL TYPE			
			DB	DB2	DB4	DM
12214	20224	Pivot Shaft	X	X	X	X
12358	20225	Linkage Hook Link	X	X	X	X
21201	20214	Governor Weight	X	X		
19858	28974	Governor Weight			X	X
22284	23858	Governor Weight			X	X
29135	30800	Governor Weight			X	
28089	28681	Governor Weight Retainer		X		
29294	29296	Governor Weight Retainer (spline)		X		
28370	28681	Governor Weight Retainer		X		
19893	23860	Governor Weight Retainer			X	X
15421	20219	Governor Arm	X	X		
24929	20219	Governor Arm	X	X		
29060	20956	Governor Arm			X	X
21312	14483	Governor Thrust Sleeve	X	X		

Identification

Identify each pump which is converted for low viscosity fuel operation by stamping "LVFC" (Low Viscosity Fuel Components) on the nameplate below the pump model number.

Warranty

Conversions for low viscosity fuel operation are made at the request and expense of the customer and as such, Stanadyne will not accept warranty claims for these modifications.

**Technical Support Group
Product Support Department**

Revision	Date	Changes
1	12:90	Defined fuel usage for both standard and low viscosity components. Added conversion parts chart.
2	1:93	Updated conversion parts chart, changed nameplate identification from "SB 125" to "LVFC".
3	6:93	Updated conversion parts chart and revised fuel usage recommendations.
4	1:98	Updated conversion parts chart.

Appendix B Cetane Numbers from FT Diesel Fuels

Study	FT Cetane Number
(Schaberg et al. 2000)	69.3
(Clark et al. 1999)	73.7
(Fanick et al. 2001)	73.6
(Frame et al. 2004)	69.3
(Cheng and Dibble 1999)	74
(Johnson et al. 2001)	74
(Sirman et al. 2000)	84

Appendix C EPA Fuels Testing Data

U4/UB/UB 12:41 FAX ZUZ3432804

EPA-Cert. & Comp. Div. -DC

001



UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
WASHINGTON, D.C. 20460

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Message: Diesel Hydrotesting results

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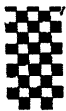


Table 1

Feedstock Properties

Feed	1	2	3	4	5
Description	Reference	Reference, Low Sulfur	80% SR	50% SR	3 Equal Parts
Composition, vol%					
SRGO	69	69	80	50	34
LCO	23	23	15	40	33
LCGO	8	8	5	10	33
°API	32.8	32.8	34.4	29.2	28.1
Sulfur, ppm	9000	5000	7500	11000	17500
Nitrogen, ppm	175	175	135	215	420
CCC est. BrNo	(4)	(4)	(2)	(5)	(13)
Cetane Number	41.6	41.6	44.5	37	35
Aromatics, vol%	35.5	35.5	30	46	46.5
PNA, vol%	19	19	15	27.5	27
Pour Point, °F	-5	-5	na	na	na
Distillation, °F					
T ₁₀	410	410	405	410	405
T ₃₀	460	460	455	465	460
T ₆₀	510	510	505	515	515
T ₇₀	560	560	555	565	565
T ₉₀	610	610	605	625	630

Table 3
Process Data for Desulfurizing Each Feed - Feed 1

Data Category	Data Element	Product Sulfur Content (ppm)		
		10	50	100
Yields (%wt on feed) (SOR/EOR)	H2S	0.96	0.95	0.95
	Plant Gas	.022/.180	.019/.182	.019/.144
	C3	.031/.097	.026/.081	.028/.077
	C4	.036/.133	.030/.112	.029/.107
	C5-373 °F	.677/1.28	0.57/1.07	.64/1.02
	Diesel Fuel	98.94/98.04	98.96/98.20	98.97/98.25
	Other	7		
Diesel Fuel Properties	Sulfur (ppm)	10	50	100
	Nitrogen (ppm)	<1	<5	<5
	Δ Aromatics (%vol)	7	6	5
	Δ PNA (%vol)	8	7	6
	Δ Cetane Number	5	4	4
	Δ API Gravity	4	3	3
	Δ Pour Point (°F)		negligible	
	Δ Distillation (°F) T	-5	-5	-5
	10%	-5	-5	-5
	30	-5	-5	-5
	50	-5	-5	-5
	70	-5	-5	-5
90	-5	-5	-5	
Inputs (as specified)	H2 (Chemical Cons.) (SCF/Bbl)	375	325	300
	H2 (Other Cons.) (SCF/Bbl)		no comment	
	Utilities: Fuel (MBTU/hr)	34.5	36.9	36.5
	Power (KWH/hr)	2250	2125	2050
	Medium Press Steam (lb/hr)	8800	8800	8800
	Cooling Water (gpm)	175	175	175
	Catalyst and Royalty (\$/BPSD)	56	45	39
	Additives (%/Bbl)		no comment	
Other Direct Costs (\$/Bbl)		no comment		
Operating Conditions	Temperature (°F)	635	635	635
	Nominal Pressure (psia)	900	875	850
	Min. Outlet H ₂ pp (psi)	500	450	400
	Actual Space Vel. (1/hr)	1	1.25	1.45
	Space Vel. (Relative to 10 ppm)	1.0	1.25	1.45
	Catalyst Life (Years)	2	2	2

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Table 3
Process Data for Desulfurizing Each Feed -- Feed 5

Data Category	Data Element	Product Sulfur Content (ppm)		
		10	50	100
Yields (%wt on feed) (SOR/EOR)	H2S	1.86	1.86	1.85
	Plant Gas	.045/.318	.038/.307	.037/.296
	C3	.065/.171	.053/.165	.051/.159
	C4	.063/.236	.061/.228	.059/.219
	C6-375 oF	1.20/2.26	1.15/2.17	1.11/2.09
	Diesel Fuel	97.95/96.36	97.98/96.43	97.98/96.49
	Other			
Diesel Fuel Properties	Sulfur (ppm)	10	50	100
	Nitrogen (ppm)	<1	<5	<5
	Δ Aromatics (%vol)	8	7.5	7
	Δ PNA (%vol)	13	12.5	11
	Δ Cetane Number	8	7.5	7
	Δ API Gravity	7	6.5	6.6
	Δ Pour Point (°F)		negligible	
	Δ Distillation (°F) T	-10	-10	-10
	10%	-10	-10	-10
	30	-10	-10	-10
	50	-10	-10	-10
70	-10	-10	-10	
90	-10	-10	-10	
Inputs (as specified)	H2 (Chemical Cons.) (SCF/Bbl)	700	675	645
	H2 (Other Cons.) (SCF/Bbl)		no comment	
	Utilities: Fuel (MBTU/hr)	27.5	28.3	29.0
	Power (KWH/hr)	3325	3250	3125
	Medium Press Steam (lb/hr)	13700	13700	13700
	Cooling Water (gpm)	225	225	225
	Catalyst and Royalty (\$/BPSD)	102	82	73
	Additives (%/Bbl)		no comment	
	Other Direct Costs (\$/Bbl)		no comment	
Operating Conditions	Temperature (°F)	636	636	635
	Nominal Pressure (psia)	900	875	850
	Min. Outlet H ₂ pp (psi)	500	450	400
	Actual Space Vel. (1/hr)	0.68	0.8	0.9
	Space Vel. (Relative to 10 ppm)	1.0	1.25	1.45
	Catalyst Life (Years)	2	2	2

Appendix D CCTM Run Script

```
#!/bin/csh -f

# RCS file, release, date & time of last delta, author, state, and locker
# $Header: /project/work/rep/SCRIPTS/src/cctm/run.cctm.jeta,v 1.8 2006/09/29 13:01:22
sjr Exp $

# ===== CCTMv4.6 Run Script
# ===== #
# Usage: run.cctm >&! cctm_e3a.log & #
# The following environment variables must be set for this script to #
# execute properly: #
# setenv M3DATA = input/output data directory #
# To report problems or request help with this script/program: #
# http://www.cmascenter.org/html/help.html #
#
=====
==== #

setenv LACIE /mnt/Data1/ACRP/LACIE/CMAQ/data/ATL_04k
setenv DataIn /mnt/Data2/ACRP/FT

#> Check that M3DATA is set:
if ( ! -e $M3DATA ) then
    echo " $M3DATA path does not exist"
    exit 1
endif
echo " "; echo " Input data path, M3DATA set to $M3DATA"; echo " "

set APPL = ft
set CFG = e3a
#set CFG = $APPL
set EXEC = CCTM_$CFG # ctm version

#> horizontal domain decomposition
#setenv NPCOL_NPROW "1 1"; set NPROCS = 1 # single processor setting
setenv NPCOL_NPROW "2 4"; set NPROCS = 8

#> for Scyld Beowulf ...
#setenv NP $NPROCS
#setenv BEOWULF_JOB_MAP -1:-1:0:0:1:1:2:2:3:3:4:4
#echo " task-processor map `beomap`"

#> Set the working directory:
set BASE = $cwd
```

```

cd $BASE; date; cat $BASE/cfg.$CFG; echo " "; set echo

#> timestep run parameters
set STDATE = 2002141 # beginning date
set JDATE = $STDATE
set STTIME = 000000 # beginning GMT time (HHMMSS)
set NSTEPS = 240000 # time duration (HHMMSS) for this run
set TSTEP = 010000 # output time step interval (HHMMSS)
set GDATE = 20020521 # to match MCIP files
set EDATE = 2002212
set OLD_DATE = 2002140

#####Loop through dates #####

#loop through all the simulation days
while( $JDATE <= $EDATE )

    set STDATE = $JDATE
    set STTIME = 000000
    set NSTEPS = 240000
    set TSTEP = 010000

#> set log file [ default = unit 6 ]; uncomment to write standard output to a log
setenv LOGFILE $BASE/logs/$APPL.$STDATE.log

#> turn off excess WRITE3 logging
setenv IOAPI_LOG_WRITE F

#> stop on inconsistent input file [ T | Y | F | N ]
setenv FL_ERR_STOP F

#> remove existing output files?
set DISP = delete
#set DISP = update
# set DISP = keep

#> output files and directories
set OUTDIR = /mnt/Data2/ACRP/FT
if ( ! -d "$OUTDIR" ) mkdir -p $OUTDIR
set CONCfile = $EXEC"CONC".$APPL.$JDATE # CTM_CONC_1
set ACONCfile = $EXEC"ACONC".$APPL.$JDATE # CTM_ACONC_1
set CGRIDfile = $EXEC"CGRID".$APPL.$JDATE # CTM_CGRID_1
set DD1file = $EXEC"DRYDEP".$APPL.$JDATE # CTM_DRY_DEP_1
set WD1file = $EXEC"WETDEP1".$APPL.$JDATE # CTM_WET_DEP_1
set WD2file = $EXEC"WETDEP2".$APPL.$JDATE # CTM_WET_DEP_2
set SS1file = $EXEC"SSEMIS1".$APPL.$JDATE # CTM_SSEMIS_1

```

```

set AV1file = $EXEC"AEROVIS".$APPL.$JDATE           # CTM_VIS_1
set AD1file = $EXEC"AERODIAM".$APPL.$JDATE         # CTM_DIAM_1
set PG1file = $EXEC"PING".$APPL.$JDATE             # CTM_PING_1
set PGDfile = $EXEC"PINGDRYDEP".$APPL.$JDATE       #
CTM_PING_DDEP_1
set PGWfile = $EXEC"PINGAERODIAM".$APPL.$JDATE     #
CTM_PING_DIAM_1
set PA1file = $EXEC"PA_1".$APPL.$JDATE             # CTM_IPR_1
set PA2file = $EXEC"PA_2".$APPL.$JDATE             # CTM_IPR_2
set PA3file = $EXEC"PA_3".$APPL.$JDATE             # CTM_IPR_3
set IRR1file = $EXEC"IRR_1".$APPL.$JDATE           # CTM_IRR_1
set IRR2file = $EXEC"IRR_2".$APPL.$JDATE           # CTM_IRR_2
set IRR3file = $EXEC"IRR_3".$APPL.$JDATE           # CTM_IRR_3

#> set ancillary log file name extensions
setenv CTM_APPL $APPL.$STDATE

#> set floor file (neg concs)
setenv FLOOR_FILE $BASE/FLOOR_${APPL}

#> set ping floor file (neg concs) [remember: env var .le. 16 chars]
setenv PLUME_FLOOR_FILE $BASE/CPLUME_FLOOR_${APPL}.$GDATE

#> horizontal grid defn; check GRIDDESC file for GRID_NAME options
setenv GRIDDESC $LACIE/GRIDDESC
setenv GRID_NAME ATL04_126X102

#> species for standard conc
#setenv CONC_SPCS "O3 NO ANO3I ANO3J NO2 FORM ISOP ANH4J ASO4I
ASO4J"

#> layer range for standard conc
#setenv CONC_BLEV_ELEV " 1 4"

#> species for integral average conc
setenv AVG_CONC_SPCS " O3 NO CO NO2 PAN HNO3 OH HO2 PAR ETH OLE
TOL XYL FORM ALD2 ISOP ASO4I ASO4J ANO3I ANO3J ANH4I ANH4J
AORGAI AORGAJ AORGPAI AORGBI AORGBJ AECI AECJ A25J ASOIL ACORS
SO2 SULF NH3"

#> layer range for integral average conc
setenv ACONC_BLEV_ELEV " 1 1"

#> input files and directories

set OCEANpath = $LACIE/emis/

```

```

set OCEANfile = ocean_file_ATL04_126X102.ncf

set EMISpath = $DataIn/
set EMISfile =
ft_egts3d_1.$STDATE.1.ATL_4k.FAA_P16_EDMS.cmaq.cb05p25tx.ncf

#set TR_EMpath =
#set TR_EMfile =

#set GC_ICpath = $OUTDIR
#set GC_ICfile = CCTM_e3aCGRID.d1b

if ( $JDATE == 2002141 ) set GC_ICpath = $LACIE/icon set GC_ICfile =
ICON_cb05_base02a.ATL04_126X102_profile
if ( $JDATE != 2002141 ) set GC_ICpath = /mnt/Data2/ACRP/FT set GC_ICfile =
$EXEC"CONC".$APPL.$OLD_DATE

set GC_BCpath = $LACIE/bcon/sens_airc/P2
set GC_BCfile = BCON_P16_CCTM46.sens_airc.NEUS4.P2.$STDATE

set METpath = $LACIE/mcipoutput/
set extn = $GDATE
set GC2file = GRIDCRO2D.4km.${extn}
set GD2file = GRIDDOT2D.4km.${extn}
set MC2file = METCRO2D.4km.${extn}
set MD3file = METDOT3D.4km.${extn}
set MC3file = METCRO3D.4km.${extn}
set MB3file = METBDY3D.4km.${extn}

set TR_DVpath = $METpath
set TR_DVfile = $MC2file

#> 7-level photolysis data w/ file header

set JVALpath = $LACIE/jproc
set JVALfile = JTABLE_${STDATE}

set AE_ICpath = $GC_ICpath
set NR_ICpath = $GC_ICpath
set TR_ICpath = $GC_ICpath
set AE_ICfile = $GC_ICfile
set NR_ICfile = $GC_ICfile
set TR_ICfile = $GC_ICfile

set AE_BCpath = $GC_BCpath

```



```

set NR_BCpath = $GC_BCpath
set TR_BCpath = $GC_BCpath
set AE_BCfile = $GC_BCfile
set NR_BCfile = $GC_BCfile
set TR_BCfile = $GC_BCfile

#> input and output files and directories (boilerplate)
source in_out.q
if ( $status ) exit 1

#> for the run control ...

setenv CTM_STDATE    $STDATE
setenv CTM_STTIME    $STTIME
setenv CTM_RUNLEN    $NSTEPS
setenv CTM_TSTEP     $TSTEP
setenv CTM_PROGNAME  $EXEC

#> look for existing log files

set test = `ls CTM_LOG_???.${APPL}`
if ( "$test" != "" ) then
  if ( $DISP == 'delete' ) then
    echo " ancillary log files being deleted"
    foreach file ( $test )
      echo " deleting $file"
      rm $file
    end
  else
    echo "*** Logs exist - run ABORTED ***"
    exit 1
  endif
endif

#> -----

env

ls -l $BASE/$EXEC; size $BASE/$EXEC

#> Executable call for single PE, uncomment to invoke
# time $BASE/$EXEC

#> Executable call for multiple PE, set location of MPIRUN script
set MPIRUN = /opt/mpich2-1.1/bin/mpirun
set TASKMAP = $BASE/machines_ft

```

```
cat $TASKMAP
time $MPIRUN -machinefile $TASKMAP -np $NPROCS $BASE/$EXEC

set OLD_DATE = $JDATE

@ JDATE = $JDATE + 1

if ( $JDATE == 2005366 ) set JDATE = 2006001

@ GDATE = $GDATE + 1

if ( $GDATE == 20020532 ) set GDATE = 20020601
if ( $GDATE == 20020631 ) set GDATE = 20020701

end #while loop over simulation days
date
```