PARTNER

Partnership for AiR Transportation Noise and Emission Reduction

An FAA/NASA/TC-sponsored Center of Excellence

Well to Wake: Life-Cycle Environmental Analyses

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Work is being conducted in collaboration with RAND.

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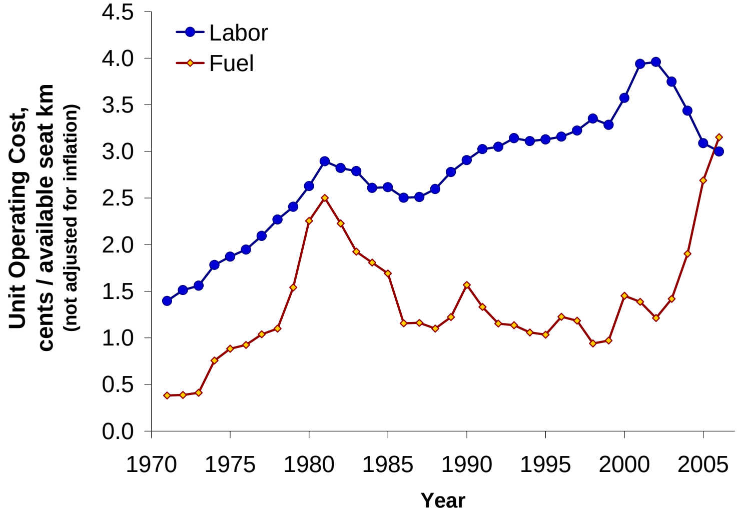
Motivation

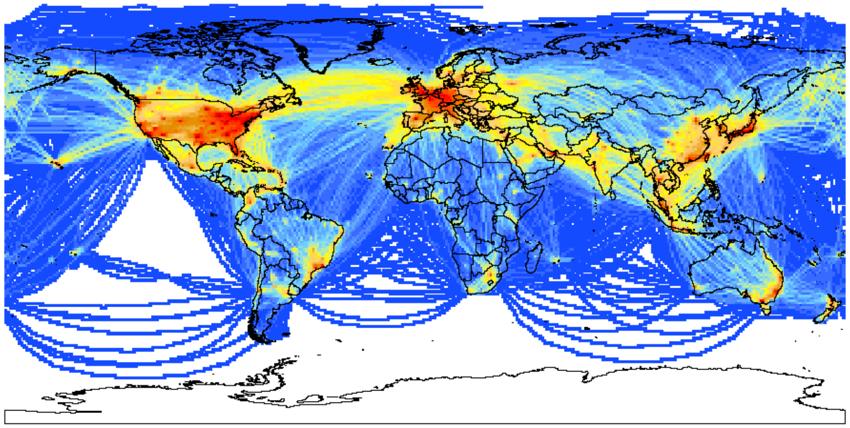
Two primary motivations for the evaluation of alternative fuels:

- The elevated level and volatility of the price of Jet A (covered in previous presentation by D. Ortiz)
- Environmental impacts of aviation on global climate change and local air quality.

Airline average unit operating costs for fuel and labor (ATA, 2007)

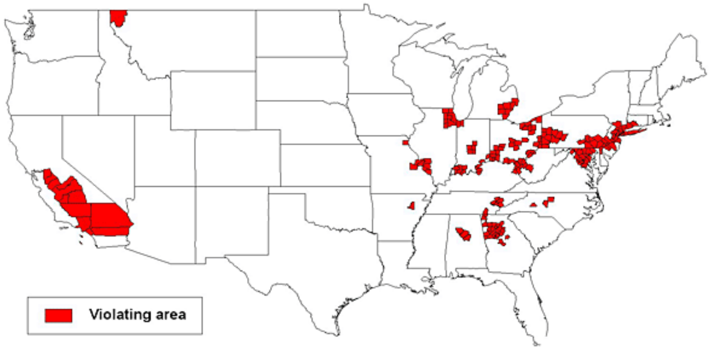


Worldwide Aviation CO_2 Emissions - 2000



Designated PM 2.5 Non-Attainment Areas as of 3-2007

U.S. EPA data interpreted by A.S.L & Assoc. Helena, MT 3/2007



Outline

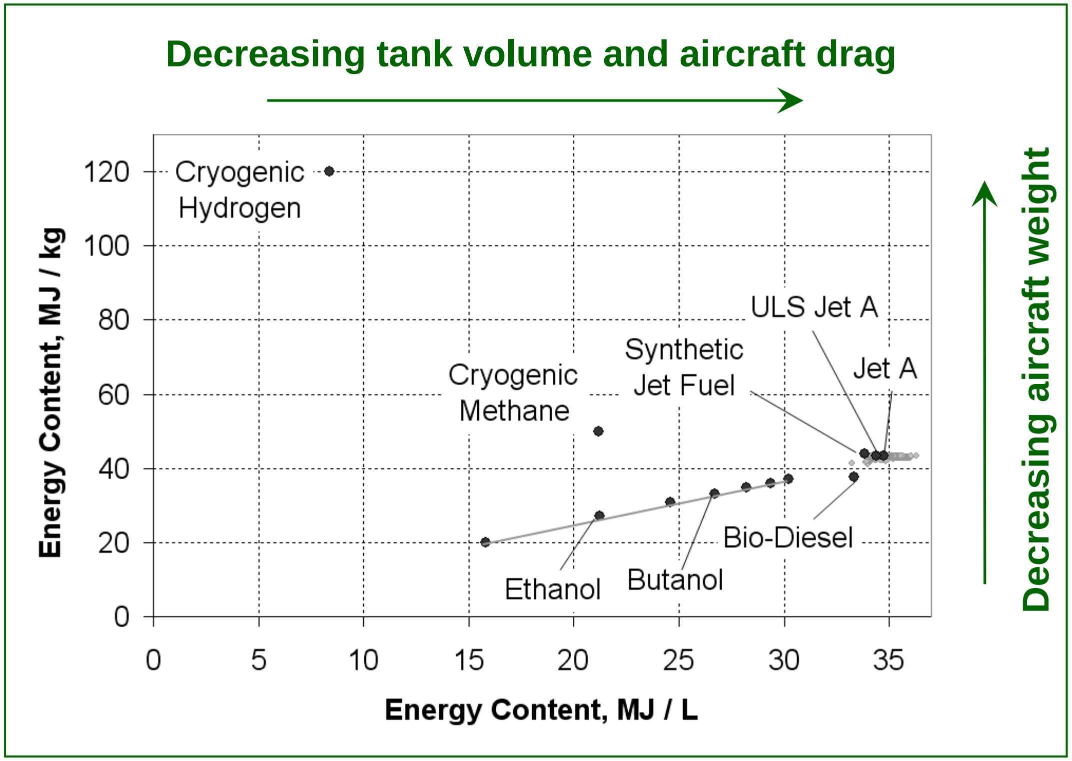
- Potential alternative fuels
- Fleet-wide alternative fuel use
- Alternative fuel emissions inventories
- Lifecycle CO_2 emissions per energy delivered to tank
- Lifecycle CO_2 emissions per payload-distance flown

Potential Alternative Fuels

Considered in terms of Energy Content

Potential fuels:

- Conventional Jet-A
- Ultra Low Sulfur (ULS) Jet-A
- Fischer-Tropsch (F-T) fuels created from natural gas, coal, or biomass
- Fuels from bio-based oils: bio-jet and bio-diesel
- Alcohols
- Cryogenic fuels (*not considered further*)



Potential feed stocks:

- Conventional oil, tar sands, very heavy oil, or oil shale → Jet A and ULS Jet A.
- Coal and natural gas → F-T fuels.
- Renewable feed stocks → F-T fuels, bio-diesel, bio-jet, and alcohols.

Potential Alternative Fuels

Considered in terms of Emissions

Potential fuels:	Chemical Composition	Aromatics	Sulfur
Conventional Jet-A	C_mH_n	under 25%	~600 ppm
ULS Jet-A	C_mH_n	under 25%	under 15 ppm
Isoparaffinic fuels • F-T fuel from natural gas, coal, biomass • Bio-jet from bio-based oils	C_mH_n	~0	under 15 ppm
Bio-diesel	$C_mH_nO_2CH_3$	0	~50 ppm
Butanol	C_4H_9OH	0	under 15 ppm
Ethanol	C_2H_5OH	0	under 15 ppm

Fuel Combustion:

Fuel + $x_1\ O_2 \rightarrow x_2\ H_2O + x_3\ CO_2$ (complete combustion)

Low aromatic fuels have reduced soot emissions

Assume sulfur in fuel is fully converted to SO_2

Aircraft Fuel Use and Combustion Emissions

Aircraft fuel weight, volume, and energy

- Scale AEDT / SAGE worldwide aircraft fuel use and emissions inventory.
- Combine Breguet range equation, fuel energy content, and aircraft performance data.
- Ignore aircraft and infrastructure modifications necessary for operation.

Cruise emissions

- Aircraft fuel weight (from above) combined with emission indices for CO_2, H_2O, NO_X, and SO_X

Local air quality emissions

- AEDT / SAGE worldwide aircraft fuel use and emissions inventory
- Takeoff fuel use scaled by ratio of energy contents
- PM scaled by change in fuel use and parameterization of soot emissions
- NO_X scaled by change in fuel use
- SO_X estimated from change in fuel use and fuel sulfur content

Fleet-wide Alt Fuel Use

Values relative to average jet fuel energy content.

Key observations:

- Range of values for Jet A reflect observed energy content variations.
- Ultra Low Sulfur Jet A requires more fuel volume, but falls within Jet A variability.
- Synthetic fuels require increased fuel volume but reduced fuel energy.
- Due to low energy content, alcohols require significantly more energy.

Fuel Type	**Fleet-wide ∆Fuel Use ***		
	Volume	**Weight**	**Energy**
Jet A (90% of JP-8)	-1.6% to 1.8%	0.5% to -0.6%	0.1% to -0.1%
Ultra Low Sulfur Jet A	1.0%	-0.3%	0.0%
Synthetic Fuel	1.6% to 4.3%	-1.9% to -2.6%	-0.2% to -0.3%
5% Biodiesel Blend, B5	0.3%	0.7%	0.1%
Butanol	36%	36%	4%
Ethanol	78%	74%	9%

*** Preliminary data, do not cite or quote**

Notes:

- Jet A range based upon 90% of sampled JP-8 data
- Synthetic Fuel data based upon range in literature
- Some flights not possible with ethanol / butanol

Cruise Emissions

Fleet-wide cruise emissions (not life-cycle emissions)

Fuel Type	ΔFuel Burn, Weight	ΔCO_2	ΔH_2O	ΔNO_X	ΔSO_X
Jet A (90% of JP-8)	0.5% to -0.6%	1.0% to -1.1%	-2.4% to 2.5%	0.5% to -0.6%	0.5% to -0.6%
Ultra Low Sulfur Jet A	-0.3%	-0.6%	1.4%	-0.3%	-97.5%
Synthetic Fuel	-1.9% to -2.6%	-3.3% to -4.7%	6.9% to 10.3%	-1.9% to -2.6%	-97.5% to -97.6%
5% Biodiesel Blend, B5	0.7%	0.2%	-0.2%	0.7%	-3.9%
Butanol	36%	2.1%	34.2%	-	-96.6%
Ethanol	74%	5.4%	66.1%	-	-95.6%

*** Values relative to mean JP-8 values**
**** Results in table are preliminary, do not quote or cite**

Alcohols are better suited for use in ground transportation because of increased energy requirement and increased water emissions.

Local Air Quality Emissions

Fleet-wide landing and takeoff emissions

Fuel Type	ΔFuel Flow, Weight	ΔNO_X	ΔSO_X	ΔPM
Jet A (90% of JP-8)	0.5% to -0.5%	0.5% to -0.5%	0.5% to -0.5%	0.5% to -0.5%
Ultra Low Sulfur Jet A	-0.3%	-0.3%	-97.5%	-14.5%
Synthetic Fuel	-1.6% to -2.3%	-1.6% to -2.3%	-97.5% to -97.6%	-14.5% to -77%
5% Biodiesel Blend	0.7%	0.7%	-3.9%	-3.2% to -16.2%
Butanol	30.4%	-	-96.7%	-
Ethanol	60.3%	-	-96.0%	-

* Values relative to mean JP-8 values from PQIS

** Results in table are preliminary, do not quote or cite

Several fuel options provide substantial SO_X reductions.

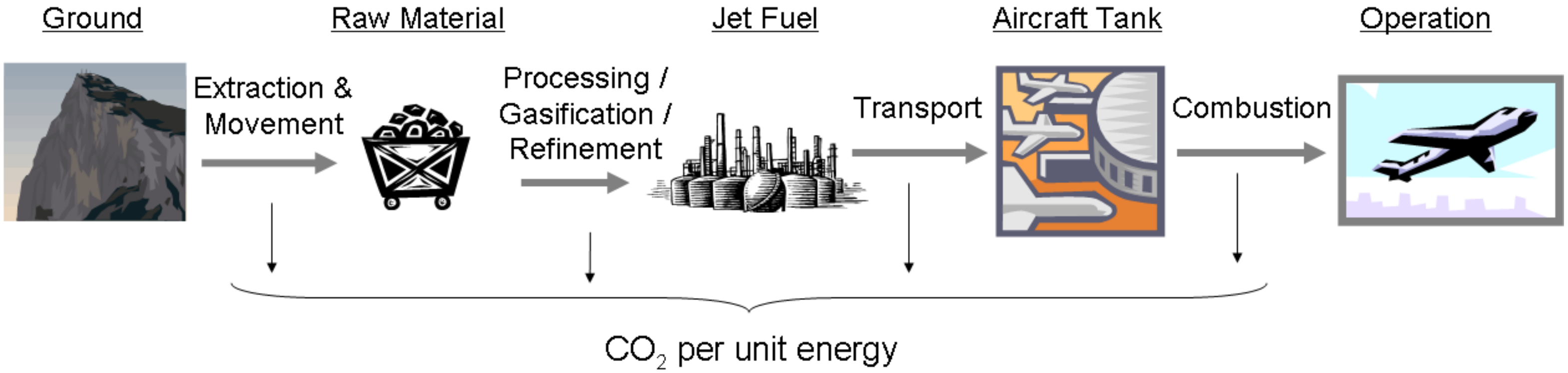
Synthetic fuels (F-T or biojet) offer potential for substantial primary PM reduction in addition to SO_X reductions.

Need to refine PM estimates based on recent measurements.

Life-cycle Carbon Dioxide Emissions

Overview

- Examining fuel life-cycle from “*well to wake*” to estimate total carbon dioxide emissions.

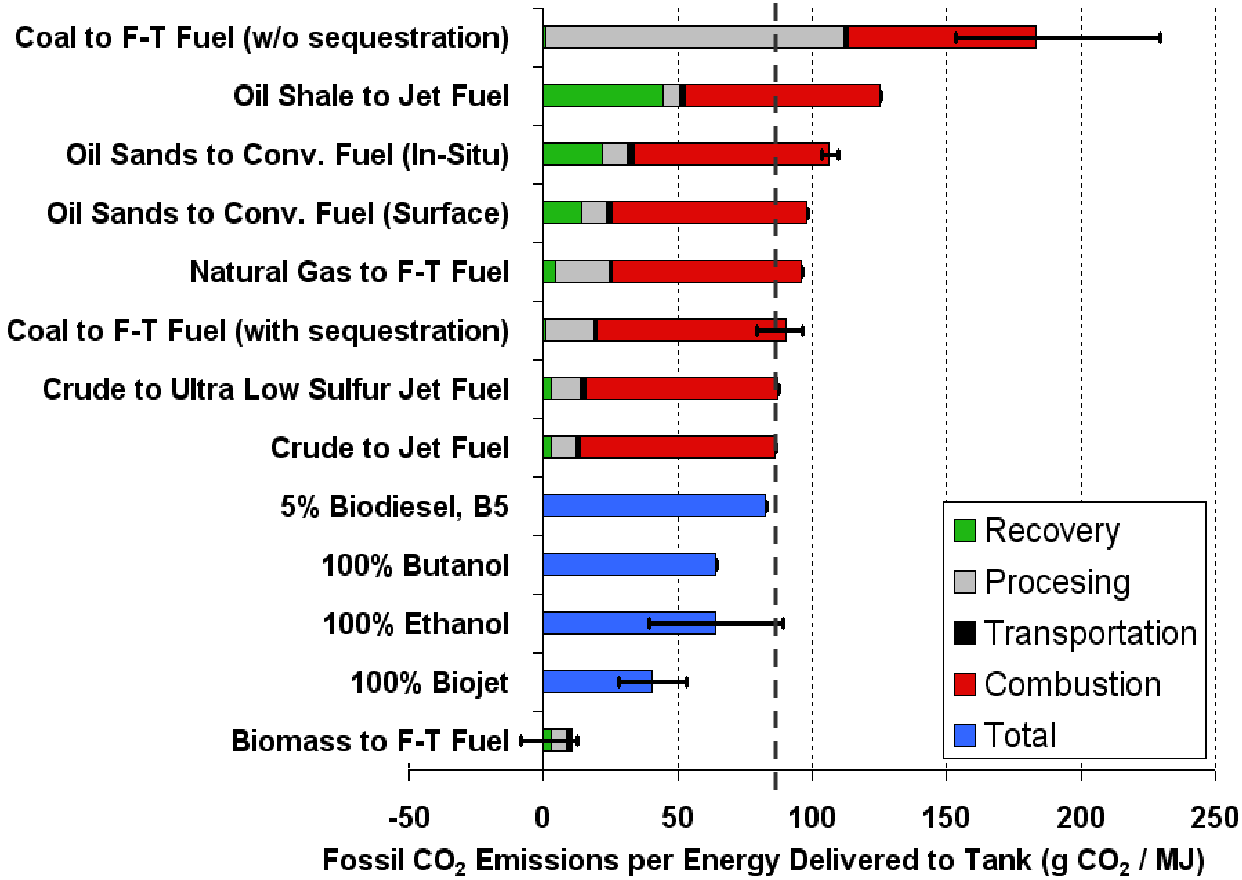


- Using Argonne National Laboratory GREET framework.
- Utilizing data from literature to find range of values for raw material energy content, process efficiencies, etc. – using data to bound lifecycle emissions.
- Modifying GREET framework to examine jet fuel (GREET designed for ground transportation).

Life-cycle Carbon Dioxide Emissions

Results on a per Energy Basis

- Fossil-based fuels and biomass-based synthetic fuels (via Fischer-Tropsch process) analyzed with GREET.
- Biodiesel, alcohols, and biojet data from literature.
- Examining biojet pathways and conducting additional sensitivity studies.



Preliminary results, do not cite or quote.

Emissions (on a per energy basis) vary according to recovery technique, processing, and biomass utilization as a feedstock.

Impact of Alternative Fuel Use on Fleet-wide CO_2 Emissions

Lifecycle carbon dioxide emissions per payload-distance flown - obtain by combining fuel use change with lifecycle CO_2 emissions.

Definition of CO_2 Intensity:

$$= \left(\frac{\text{Energy Use}}{\text{Payload * Distance}} \right) (\text{Energy Ratio}) (\text{Lifecycle } CO_2)$$

$$= \left(\frac{MJ_{\text{Jet A}}}{kg \cdot km} \right) \left(\frac{MJ_{\text{Alt Fuel}}}{MJ_{\text{Jet A}}} \right) \left(\frac{g\ CO_2}{MJ_{\text{Alt Fuel}}} \right) = \frac{g\ CO_2}{kg \cdot km}$$

Jet A CO_2 Intensity:

U.S. commercial fleet achieved 0.015 MJ / kg-km in 2005

$$= \left(0.015 \frac{MJ_{\text{Jet A}}}{kg \cdot km} \right) (1) \left(86 \frac{g\ CO_2}{MJ_{\text{Jet A}}} \right) = 1.3 \frac{g\ CO_2}{kg \cdot km}$$

CO_2 Intensity of 1.3 g CO2 / kg-km for U.S. fleet in 2005

Life-cycle Carbon Dioxide Emissions

Results on a per Payload-Distance Basis

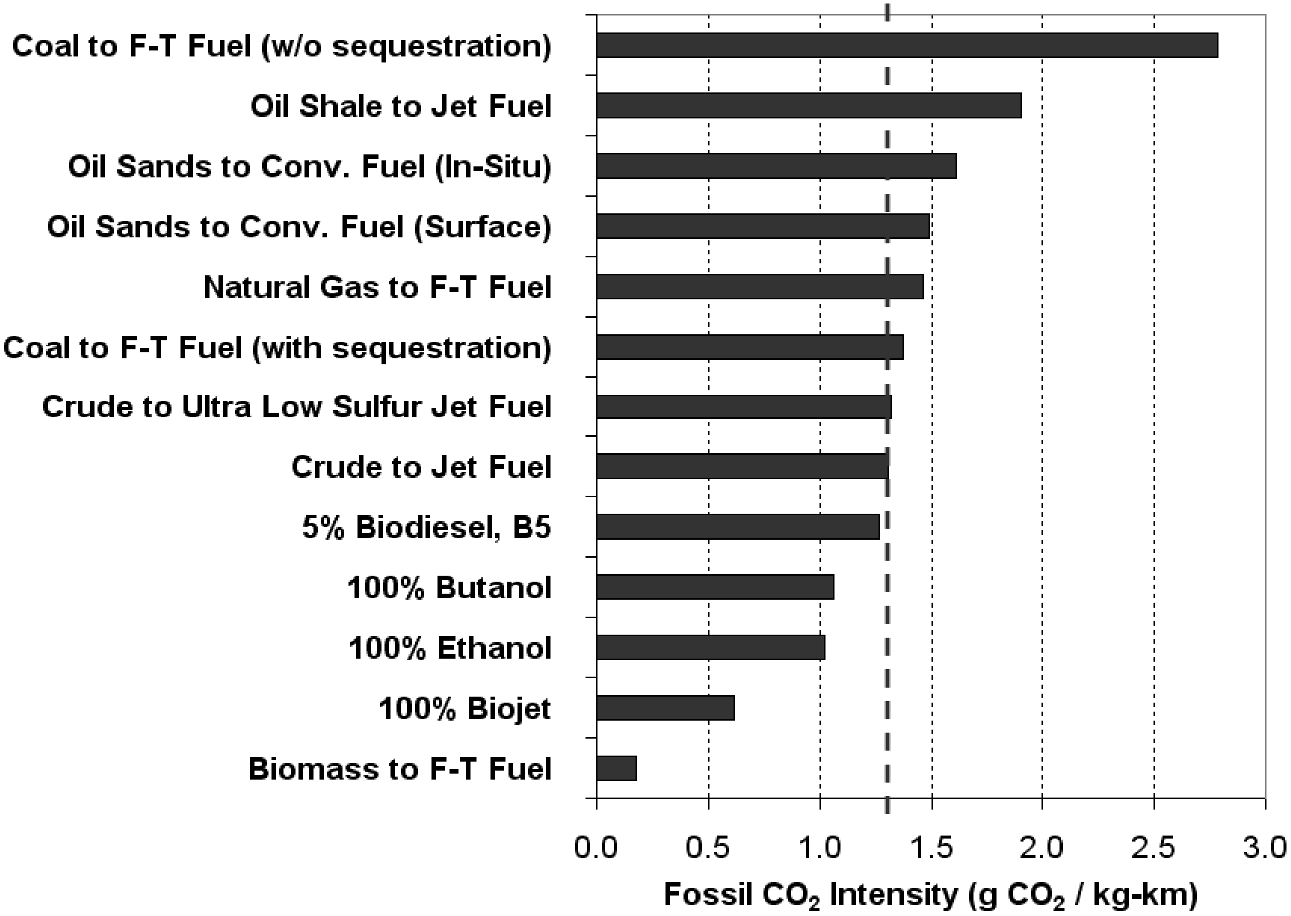
Fossil CO_2 Intensity

Metric captures:

- Life-cycle carbon dioxide emissions.
- Fuel chemistry.
- Change in energy required due to fuel weight differential.

Working to include:

- Sensitivity studies.
- Multiple biojet pathways.



Preliminary results, do not cite or quote.

Substantial carbon dioxide reductions possible with use of biomass-based fuels.

Summary

- Because of increased energy use and atmospheric water emissions, alcohols provide larger net GHG benefit when used in ground transportation (as compared to aviation).
- Coal-to-liquid fuels (via F-T process with CCS) have comparable lifecycle CO_2 to conventional Jet A and their use could improve local air quality. Without CCS, lifecycle CO_2 will double.
- Alternative fuels exist that could both reduce lifecycle CO_2 and improve local air quality (e.g., biojet and biomass-to-liquids via F-T process), but …

  … at present the ability to produce these fuels is limited by resource constraints and at present the costs of production are higher than conventional fuels.
- Could improve air quality in the near-term with reduced sulfur Jet A.

Next Steps

- Complete life-cycle CO_2 emissions assessment.
- Refine emissions inventory estimates.
- Examine impact of alternative fuel use on global climate change and local air quality using APMT (FAA tool suite).
- Extend analysis to alternative fuel use in ground service equipment and other airport uses of alternative fuels.

References

- Argonne National Laboratory, “The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model Version 1.7,” http://www.transportation.anl.gov/software/GREET/, February 2007.
- Boeing Company, “Airport Planning Guides” (737, 747, 757, 767, 777), http://www.boeing.com/assocproducts/aircompat/plan_manuals.html/.
- Embraer Commercial Jets, “ERJ145 Spec Sheet,” http://www.embraercommercialjets.com/.
- Environmental Protection Agency Office of Transportation and Air Quality, “Greenhouse Gas Impacts of Expanded Renewable and Alternative Fuels Use,” EPA420-F-07-035, April 2007.
- Neste Oil, “NExBTL, second generation renewable diesel,” http://www.nesteoil.com/.
- Petroleum Quality Information System (PQIS), Defense Energy Support Center, DESC-BP:20031115, 2005.